
Supplementary information

A seafood risk tool for assessing and mitigating chemical and pathogen hazards in the aquaculture supply chain

In the format provided by the
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Supplement 1

1.1 Current aquaculture production and sub-sector projection to 2050

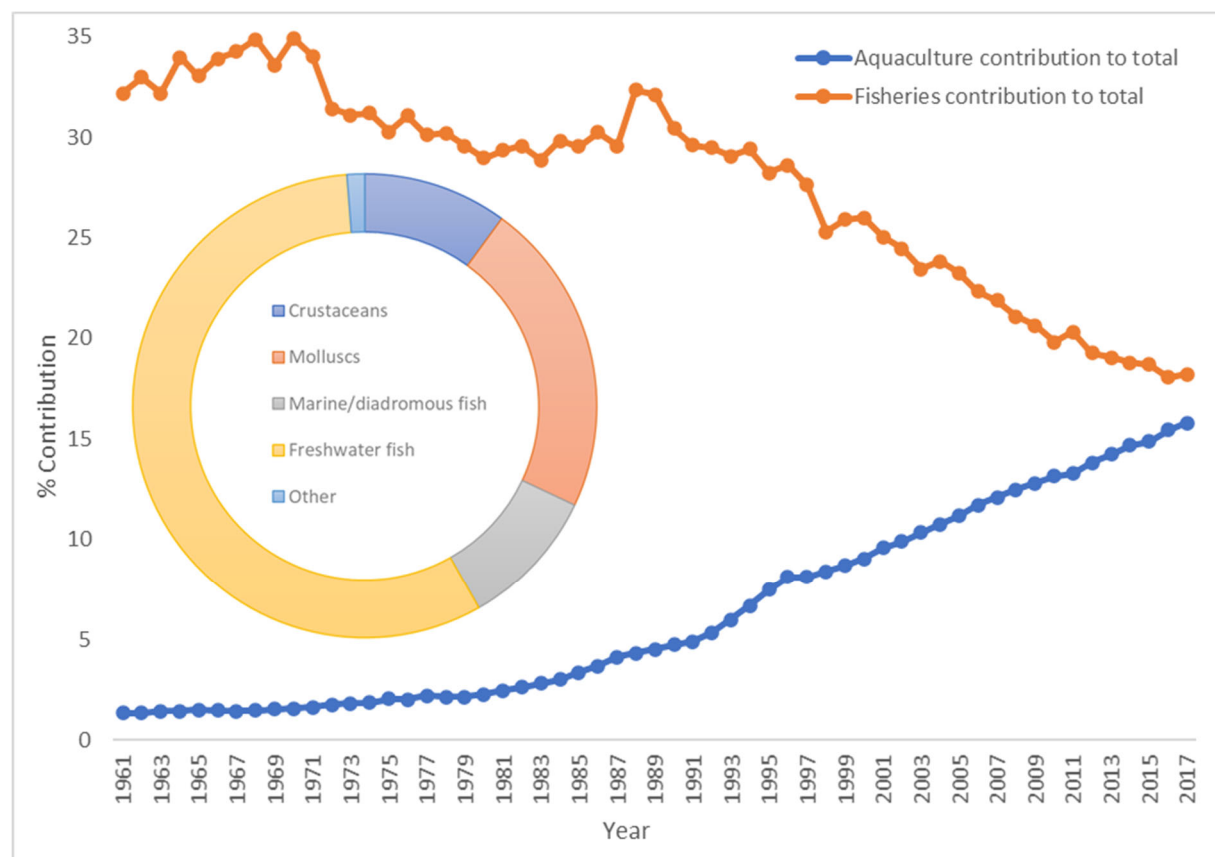


Fig. S1.1. Contribution of global capture fishery and animal aquaculture production to total (aquatic and terrestrial) animal production between 1961 and 2017. Data for terrestrial animal production derived from FAOSTAT: <http://www.fao.org/faostat/en/#data/QL>. Data for capture fishery and aquaculture derived from FAO FIGIS database: <http://www.fao.org/fishery/topic/16140/en>. Inset doughnut diagram – Profile of global production of aquatic animals from aquaculture in 2016 was approximately 80 million tonnes (Mt), comprising 43.5 Mt freshwater fish, 16.7 Mt molluscs, 7.7 Mt crustaceans, 7.5 Mt marine fish and almost 1Mt of other aquatic animal taxa (including sea cucumbers, sea urchins, turtles, frogs, and edible jellyfish). Data for proportional contribution of aquaculture to global animal production does not include production metrics for aquatic plants and seaweeds, which contributed a further 31.6 mmt to total aquaculture production in 2016.

1.2 Historic and projected growth by sub-sector to 2050

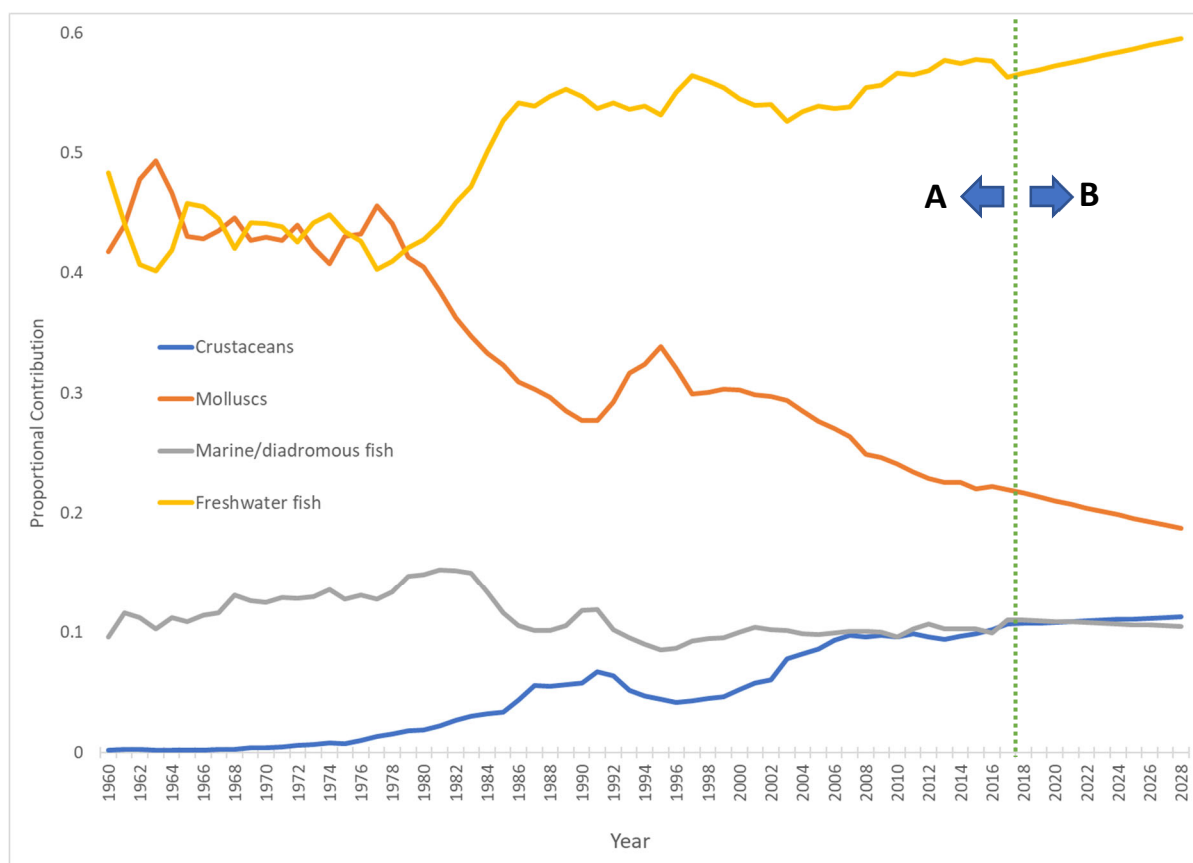


Fig. S1.2. Proportional contribution of production from animal aquaculture sub-sectors to total animal aquaculture. (A) Based upon empirical data for the period 1961 to 2017 within the FAO FIGIS database: <http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en>; (B) Projected production for the period 2019 to 2028 using OECD/FAO fish and seafood outlook projections (see [2]) from which we have inferred c.1% per annum growth in mollusc production, c.2% per annum growth in marine finfish production and c. 3% per annum growth in crustacean and freshwater fish production. Here, freshwater fish and crustaceans increase their proportional contribution to overall seafood aquaculture production, marine fish proportional contribution remains relatively stable while proportional contribution of molluscs decreases.

1.2.1 Seafood from marine fish aquaculture

Capture fisheries and aquaculture supplied 80 Mt of marine fish to the global seafood market in 2018. Approximately 8Mt from aquaculture and the remainder from fishing. Although no marine fish species are within the top 10 farmed species by volume, Atlantic salmon are the second most valuable species farmed in global aquaculture (US\$ 16.7bn in 2017) [3]. Excluding data from China (where production is dominated by freshwater species), milkfish and various marine perciform species (e.g., sea bass) comprise significant sectors that are likely soon to become top 10 species groups [3].

1.2.2 Seafood from freshwater fish aquaculture

Capture fisheries and aquaculture supplied 60 Mt of freshwater fish to the global seafood market in 2018; the majority (47 Mt) from aquaculture [1]. Carps, barbels and other cyprinids were the top global aquaculture species by volume (28.3 Mt) and value (US\$ 61.4bn) in 2017; Tilapias and other cichlids, catfishes and freshwater perciform fishes also ranked in the top 10 [3]. Low relative cost of production based on efficient assimilation of plant-based dietary ingredients and the use of basic culture

technologies accessible to farmers in low- and middle-income (LMIC) nations have supported this rapid growth and a prominent role in nutritional security and poverty alleviation [4].

1.2.3 Seafood from Crustacean aquaculture

Capture fisheries and aquaculture supplied 15.4 Mt of crustaceans to the global seafood market in 2018; the majority (9.4 Mt) from aquaculture [1]. White leg shrimp (*Penaeus vannamei*) is the most valuable farmed species across all aquaculture sectors – farmed in 36 countries and contributing 4% of global aquaculture production by volume and almost 11% by value (US \$26.7 bn) in 2017 [3]. Chinese mitten crabs (*Eriocheir sinensis*) and Red Swamp Crayfish (*Procambarus clarkii*) - both predominantly farmed in China - contributed a further 8% (US \$20bn) of total aquaculture value in 2017 [3]. Together, decapod crustaceans comprised 21% (US \$54bn) of global aquaculture production value in 2017 – a value share reflecting the high relative unit price of crustacean seafood [3].

1.2.4 Seafood from Molluscan aquaculture

Capture fisheries and aquaculture supplied 23.7 Mt of molluscs to the global seafood market in 2018; the majority (17.7 Mt) from aquaculture [1]. Twelve species of oysters farmed in 44 countries contributed approximately 5% of global aquaculture by volume (5.7 Mt) and 3% by value (US \$6.8bn) in 2017. Clams, cockles and arkshells made similar contributions in terms of quantity, albeit at higher value (5.6 Mt, US\$ 9.8bn) while mussels (1.25 Mt, US\$ 3.8bn) were also a significant element of global production [3]. Over 25 Mt of global aquaculture output is not fed (so-called 'extractive') – marine bivalve molluscs predominating [1].

Supplement 1 References

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SUPPLEMENT 2

2.1 Interaction and impact of chemical and microbial hazards on seafood

2.1.1 Marine fish

Marine fish osmoregulate by drinking seawater and excreting excess salts via their gills and urine. Seawater intake and food ingestion causes uptake of natural and anthropogenic chemical contaminants via epithelial cells of the gill and gut – which for lipophilic compounds can lead to their bioaccumulation [1] and biomagnification (if consumption of contaminated lower trophic level prey occurs) [2]). Tissue tropism depends on kinetic properties of specific contaminants but includes edible components of seafood such as musculature, skin [3] and liver [4]. Land- and air-based sources dominate the supply of chemical contaminants to marine systems [5] but natural organometallic toxins (e.g., methyl mercury) and organic biotoxins from microbes (e.g., phycotoxins) also occur; collectively impacting animal health and contaminating products destined for human consumption [6]. Chemical profiles in wild marine fish reflect point-sources of pollution but also life histories (migration, trophic status) of specific taxa [7]. Profiles in fish from marine aquaculture may reflect the local environment [8] or the composition of the feed consumed - fish meal or fish oil (FMFO) potentially translocating contaminants from distant point sources to the farm [9]. Increasing marine fish aquaculture in offshore locations [10] may break the link between point-source pollution and chemical contamination of marine fish seafood - however, feeds containing FMFO, particularly those obtained from species which biomagnify contaminants, will remain an important challenge for controlling chemical contamination in seafood from these systems.

Infectious disease agents are serious hazards to marine fish production [11, 12] – placing strain on local-global supply chains and providing obstacles to trade. Emerging diseases are frequent – causing mass mortality (e.g., ISA in salmon [13, 14]) or slow growth syndromes (e.g., *Enterospora* sp. in sea bream [15]). Accelerating forcing factors acting on marine systems (climate change, habitat loss etc.) are being attributed to disease emergence and epidemics in marine animals [16], including for potentially zoonotic pathogens [17]. Since disease agents impacting marine fish aquaculture systems invariably emerge from wild host reservoirs [18], improved profiling of wild and farmed marine fish diseases with potential to impact supply chains will be needed to safeguard production from both sectors.

Human illnesses caused by anthropogenically-derived pathogens have been associated with ingestion of marine fish, including diarrheal agents (e.g., *E. coli*) and other pathogens from human–animal reservoirs (e.g., *Campylobacter*) [19]. Contamination during production- and harvest-phases may be further exacerbated during processing [20]. Anthropogenic-derived pathogens are released to water courses via discharge points for domestic or agricultural effluents [21]. Although offshore marine environments offer significant dilution potential, production near heavily urbanised areas will enhance potential for exposure. Similarly, contamination with environmental pathogens (such as human pathogenic *Vibrio* spp.) can occur in fish produced in marine and brackish systems, be exacerbated by processing, and can lead to serious clinical outcomes in human consumers [22].

2.1.2 Freshwater fish

Freshwater fish osmoregulate by active uptake of salts from water and food and, excretion of hypotonic urine to balance water absorption through the skin. Despite fundamental physiological differences to marine fish, processes governing uptake of chemical contaminants, bioaccumulation, biomagnification, and tissue tropism of specific contaminants, are similar. In context with potential sectoral expansion in coming decades, industrial and agricultural effluents containing chemical pollutants, combined with other pressures from urbanisation [23] will present new barriers to safe food production from freshwater systems. Heavy metals, persistent organic pollutants, and other

chemicals present in urban waste streams can be detected in organs and tissues of farmed freshwater fish [24, 25]. In addition, veterinary medicine residues including antibiotics [26] and hormones [27] used in early life- and growout-phases can accumulate in tissues and affect safe trading and consumption [28, 29]. The transmission of antimicrobial-resistant (AMR) microbes via freshwater fish seafood is also of concern [30]. Naturally produced cyanobacterial toxins which impact fish health and survival during production can accumulate in edible components destined for food [31]. Prokaryote blooms which generate toxins are driven by nutrient pollution arising from land-based sources – a phenomenon likely exacerbated by the impact of climate change on freshwater systems [32].

Diseases can significantly disrupt freshwater fish aquaculture. Intensification of farming systems and inherent vulnerability in health of cold-blooded animals to the effects of climate change [33] have driven emergence of highly pathogenic viral [34], bacterial [35] and parasitic [36] diseases which impact yield and profit, particularly in LMIC nations [37]. Freshwater salmonid production in temperate freshwaters have been stalled by diseases such as proliferative kidney disease (PKD) [38] while syndromic conditions have implicated skin health and in turn, industry performance and product marketability [39]. Freshwater life stages of Atlantic salmon have been impacted by Salmonid alphavirus 1 [40] while metazoan parasites (e.g., *Gyrodactylus salaris*) infecting farmed salmonids can be transferred to wild susceptible hosts, potentially requiring drastic intervention strategies for their control [41].

Seafood from freshwater fish can become contaminated with environmentally- and anthropogenically-derived pathogens [42]. Some bacterial pathogens (e.g., *Clostridium botulinum*) are natural constituents of freshwaters and may cause gastrointestinal illness in consumers [43]. Others (e.g., *Salmonella* spp.) are common in sewage and able to induce illness following consumption of contaminated freshwater fish [44]. Infective life stages of zoonotic parasites present in flesh can transmit to humans via consumption of raw or undercooked freshwater fish products – including the tapeworm *Diphyllobothrium* spp. [45].

2.1.3 Crustaceans

Marine decapods osmoregulate by restricting water loss and ion gain while freshwater species do the opposite - gill and gut epithelial cells performing these functions, often differentially during discrete stages of development [46]. Exposure of farmed crustaceans to chemical hazards is dependent on location of farm sites relative to point sources of pollution [47], the contaminant profile of feeds [48], the effect of prevailing physico-chemical and climatic conditions on contaminant availability [49] and, specific life history traits of the species under consideration [50]. Capacity for biotransformation and bioaccumulation of chemical pollutants may differ markedly between invertebrate and vertebrate taxa – leading to variations in direct toxicity to the host [51] and in tissue concentrations, even when different species are sampled from the same location [52]. Risk assessments applied to seafood supply chains must therefore reflect the nuanced capacity for biotransformation and accumulation in specific species and, the propensity for contaminants to locate to edible components destined for human consumption [53]. Despite this, basic research on the direct health impact, biotransformation, and bioaccumulation of known and (particularly) emerging chemical contaminants in commercially farmed crustacean species, is lacking [54]. Allergens are natural compounds associated with the musculature and carapace, that can cause illness (including severe anaphylaxis) in consumers of crustacean seafood [55]. The prevalence of allergy to crustacean seafood is almost certainly underestimated - in the USA it is a significant health concern affecting over 6m people, twice as common as peanut allergy [56].

Disease presents a significant barrier to seafood supply from crustacean aquaculture [11]. Viral pathogens have hampered regional production of penaeid shrimp [57], with potential for global pandemics linked with trade in infected live animals and products [58]. Bacterial pathogens, including those where disease is associated with expression of toxin-coding genes (e.g., AHPND) have collapsed production of shrimp in some Asian nations [59]. Parasitic diseases like *Enterocytozoon hepatopenaei*

(EHP) underlie chronic production losses, often manifested as complex syndromes affecting growth, yield and profit [60]. In contrast to fish, conventional vaccination strategies are not available for invertebrates – biosecurity strategies which minimise contact between pathogen and host the primary means of risk reduction [61].

Crustaceans grown in temperate or tropical marine and brackish waters are exposed to environmental microbes such as *Vibrio* spp. Clinically relevant taxa, including pathogenic strains of *V. vulnificus*, [62] and *V. parahaemolyticus* [63] have been detected in retail and supermarket shrimp products, with the potential for rapid proliferation during post-harvest phases, particularly if appropriate cold chain controls are not applied [64]. Exposure to sufficient infectious dose coupled with potential for antimicrobial resistance [63] of clinically relevant *Vibrio* taxa pose significant risks to humans via contact and consumption – infection leading to gastro-enteritis, septicaemia and even death in some cases [65]. Crustaceans from marine and freshwaters can become contaminated with anthropogenically-derived pathogens during production, harvest, and preparation. *Salmonella* spp. contamination is frequently reported associated with consumption of crustacean seafood - restricting loadings in shrimp ponds necessary to prevent proliferation during post-harvest phases [66]. Zoonotic pathogens pose significant risk to human consumers – trematode parasites of the genus *Paragonimus* excyst following consumption of raw or undercooked crab and crayfish flesh - progressing to lung infection and tuberculosis-like symptoms in over 1m people annually [67].

2.1.4 Molluscs

Bivalves obtain food by filter-feeding microbes and organic content from water – a trait simultaneously underlying their potential as autogenic engineers [68], focal organisms for extractive aquaculture [12] and, as bioaccumulators of diverse chemical and pathogen hazards from aquatic environments [69]. Despite a low trophic position, bivalves may disproportionately accumulate certain contaminants, driving biomagnification through food chains – including for heavy metals [70] and PCBs [71]. Other chemicals (e.g., PAHs) which accumulate in bivalves may be metabolised in the liver of co-habiting higher trophic level vertebrates, catalysing significant negative biological effects, including cancer [51] – posing similar potential risk to human consumers of molluscs collected from contaminated sites [72]. Algal blooms are important food sources for bivalves but may also deliver phycotoxins which impact their health [73]. Phycotoxins, many thermostable during cooking, can accumulate to cause illness upon consumption [6] and, significant delays in the ability to harvest molluscs from affected growing sites [74]. Other emerging toxins (including tetrodotoxin, TTX) have been detected in mollusc flesh [75] highlighting a need for vigilance in monitoring for novel and emerging biotoxins in molluscan seafood.

Filter-feeding exposes bivalves to wide-ranging viral, prokaryote and, eukaryote pathogens which can impact health and survival during production. Disease incursions in high-output mollusc hatcheries have caused catastrophic mortalities implicating larval supply to growout phases [76]. In certain sectors (e.g., hatchery-supplied oysters) disease has impacted farm yield and profit [77] - whereas sectors relying on naturally settled mollusc seed apparently report lower levels of disease [78]. The farming of molluscs in areas where listed diseases are endemic or unknown may impact international trade in live animals unless adequate controls are in place [79].

Bivalves can concentrate human pathogens within their viscera during primary production - posing significant public health risks when animals are eaten raw [3]. Notwithstanding sanitary controls in place in many nations, outbreaks of viral borne illness (e.g., human norovirus, hepatitis A virus) are relatively frequent – for example around one sixth of food-borne norovirus illnesses in the UK are attributed to oyster consumption [80]. Large focal outbreaks can also occur – including the largest recorded seafood-borne outbreak involving 300,000 people developing hepatitis A-associated illness after consuming raw clams from sewage contaminated waters in China [81]. Bacterial pathogens pose a similar risk – numerous taxa including *Salmonella* spp., toxin producing *Escherichia coli*, and *Shigella*

spp. being detected in molluscs destined for human consumption [19, 20, 42]. Aquatic bacterial and eukaryotic microbial taxa occurring naturally in bivalve growing waters can contaminate animals during production – potentially proliferating during post-harvest phases. Members of the genus *Vibrio* are perhaps most significant, frequently implicated in outbreaks following mollusc seafood consumption [42]. Their preference for warm, brackish waters underlines concerns for increased risk of *Vibrio*-induced seafood illness concomitant with warming oceans [82].

2.2 The Seafood Risk Tool (SRT)

2.2.1 Phases in seafood supply

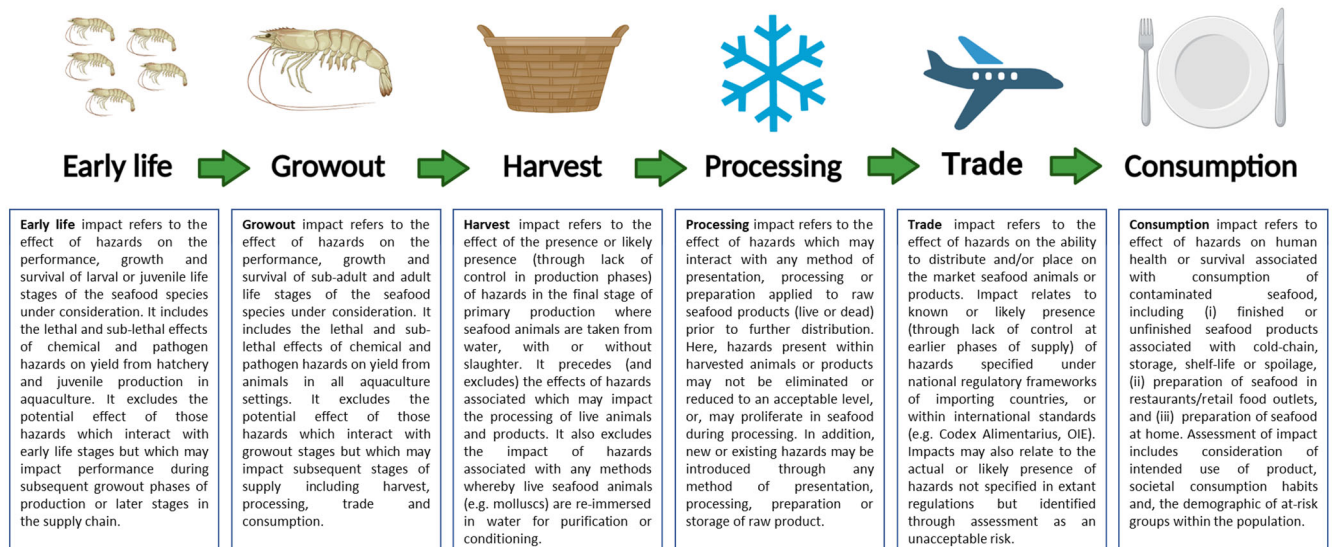


Figure S2.1. Definitions of seafood supply phases considered in the Seafood Risk Tool (SRT) and descriptions of potential for hazards to interact with discrete phases of the seafood supply chain. Early life-, growout- and harvest-phases define the production components of supply, after which animals are processed (to be consumed live or otherwise processed to products), traded (locally, nationally, internationally) and consumed (in various states from raw to cooked).

2.2.2 The *Seafood Risk Tool (SRT) schema*

Impact scores for the 14 specific hazard categories (main text, **Table 1**) and customised hazard list per aquaculture scenario, interacting with discrete phases of the seafood supply chain, (**Figure S2.1**) are calculated as a multiple of the 'severity of harm' (Part 1) and the 'likelihood of occurrence' (Part 2) according to **Table S2.1**, below.

Score	Part 1: Severity of harm	Part 2: Likelihood of occurrence
1 [Negligible]	Zero or negligible negative impact on the health or survival of animals in production, the ability to harvest, the effect on product or animals in processing, the trade of live animals or seafood products, or the health or survival of humans consuming products or animals	Negligible likelihood of occurrence of hazard resulting in harm* *No empirical evidence
2 [Very low]	Minimal and transitory negative impact on the health or survival of animals in production, the ability to harvest, the effect on product or animals in processing, the trade of live animals or seafood products, or the health or survival of humans consuming products or animals	Very low likelihood of occurrence of hazard resulting in harm* *Isolated empirical cases
3 [Low]	Low but noticeable, short-lived negative impact on the health or survival of animals in production, the ability to harvest, the effect on product or animals in processing, the trade of live animals or seafood products, or the health or survival of humans consuming products or animals	Low likelihood of occurrence of hazard resulting in harm* *Low numbers of spatially and temporally discrete empirical cases
4 [Medium]	Noticeable and moderately sustained negative impact on the health or survival of animals in production, the ability to harvest, the effect on product or animals in processing, the trade of live animals or seafood products, or the health or survival of humans consuming products or animals	Medium likelihood of occurrence of hazard resulting in harm* *Numerous spatially and temporally separated empirical cases
5 [High]	Very significant and long term or persistent negative impact on the health or survival of animals in production, the ability to harvest, the effect on product or animals in processing, the trade of live animals or seafood products, or the health or survival of humans consuming products or animals	High likelihood of occurrence of hazard resulting in harm* *Many spatially and temporally separated empirical cases
6 [Very high]	Catastrophic impact on the health or survival of animals in production, the ability to harvest, the effect on product or animals in processing, the trade of live animals or seafood products, or the health or survival of humans consuming products or animals	Very high likelihood of occurrence of hazard resulting in harm* *Extensive spatial and temporal empirical cases

2.3 The Seafood Risk Tool (SRT) applied to bivalve mollusc aquaculture scenario

(See separate Excel datasheet containing data for SRT application by expert sub-groups, as detailed in main text)

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