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

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Intricate links between aquatic animals and their environment expose them to chemical and pathogenic hazards, which can disrupt seafood supply. Here we outline a risk schema for assessing potential impacts of chemical and microbial hazards on discrete subsectors of aquaculture—and control measures that may protect supply. As national governments develop strategies to achieve volumetric expansion in seafood production from aquaculture to meet increasing demand, we propose an urgent need for simultaneous focus on controlling those hazards that limit its production, harvesting, processing, trade and safe consumption. Policies aligning national and international water quality control measures for minimizing interaction with, and impact of, hazards on seafood supply will be critical as consumers increasingly rely on the aquaculture sector to supply safe, nutritious and healthy diets.

Seafood arising from animals encompasses a vast array of invertebrate and vertebrate species captured from, and grown in, marine, fresh, brackish and indoor recirculating water systems. Combined production from fisheries and aquaculture amounted to over 180 million tonnes in 2017. Rapid growth in aquaculture has increased its contribution to total aquatic food production (now ~50%) and to overall global animal production, with over 400 different species being farmed (Supplementary Section 1.1 and Supplementary Fig. 1.1). In the next three decades, increased demand for aquatic protein as a component of human diets is predicted, requiring a doubling of output from global aquaculture as capture fisheries remain stable[1]. By 2050, at least 100 million tonnes of extra seafood, predominantly arising from aquaculture, will be placed on the market (Supplementary Section 1.2 and Supplementary Fig. 1.1). Differential projected growth in the four major subsectors of animal aquaculture—marine fish, freshwater fish, crustaceans and molluscs—is expected to consolidate freshwater fish as the dominant contributor to global seafood, with more modest but nonetheless substantial expansions in supply from the other three subsectors (Supplementary Section 1.2 and Supplementary Fig. 1.2). In this Analysis, we propose that pathogen and chemical hazards present in aquatic systems have the potential to severely limit production, or safe consumption, of seafood arising from aquaculture. The Seafood Risk Tool (SRT) described here allows detailed profiling of the uncontrolled and controlled impact of these diverse hazards at six key phases in the seafood supply chain. When applied to specific national or subnational aquaculture scenarios (for example, for production of a given species from a defined location, with products destined for designated markets and end uses), the SRT can perform a critical function for national governments by supporting conditions for high animal health status and conditions for trade and safe consumption—core components of the One Health approach to aquaculture[2] and integral within strategies aiming to nourish nations with 'blue foods' (defined in ref. [3]).

Hazards and seafood. Aquatic animals have a particularly intricate relationship with their environment—their physiology and life-history traits making them prone to exposure, accumulation and impact of diverse chemical and pathogen hazards present in water, sediments and their food. The SRT considers three broad hazard categories with the potential to interact with, and impact, the seafood supply chain from different aquaculture subsectors: (1) chemical hazards (CH) from natural or anthropogenic sources that may affect the health or survival of animals used for seafood, and humans consuming seafood products; (2) animal pathogen hazards (AH) that may affect the growth, performance, survival or product quality of animals destined for use as seafood; (3) human pathogen hazards (HH) associated with seafood that may affect the health and survival of human consumers. Analysis of the literature associated with hazard interaction with, and impact on, different seafood species groups (Supplementary Section 2.1), augmented with information on chemical and pathogen categories listed in international aquatic animal health and seafood safety guidelines[4,5], proposed 14

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hazard subcategories within CH, AH and HH. Further definition of hazards falling within these subcategories (for example, specific animal and human pathogen taxa, anthropogenic chemical species, natural biotoxins and allergens) then forms a customized hazard list relevant to specific aquaculture scenarios, taking account of farmed species, farm location and method, intended market and product end use. Hazard subcategories and empirical illustrations of interaction between specific hazards and aquatic animals used for seafood are presented in Table 1 and, for representative marine fish, freshwater fish, crustacean and mollusc seafood groups, in Supplementary Section 2.1.

Pathogen and chemical hazards interact differentially with discrete phases of the supply chain, through early life (for example, hatchery production of larvae), grow-out (where juvenile and adult animals are grown in farm settings), harvesting, processing (to products), trading (nationally or internationally) and, eventually, consumption (in different forms). While the impacts of pathogen and chemical hazards on production phases are usually economic (for example, slow growth or mortality of stock, poor animal welfare and costs associated with therapies), those affecting processing, trade and consumption phases may be economic (where they may limit processing efficiency and restrict trade or the capacity to place products on the market) or health related (where intake of hazards via seafood consumption has public health consequences) (Supplementary Section 2.2 and Supplementary Fig. 2.1). Regardless of where in the supply chain hazards interact and impact, collectively they translate to a loss of supply of (safe and sustainable) food—a crucial consideration to be factored into future production aspirations at national, regional and global levels. Estimating the impact of specific hazards at given phases of supply also facilitates focus on those phases where interventions for control may have the greatest impact. The SRT may therefore be applied in three control states: (1) when assessing the potential uncontrolled impact of hazards acting upon supply from a specific aquaculture scenario; (2) when assessing benefit of applying discrete phase-specific control measures for limiting impact of hazards acting at that phase of supply; (3) when assessing multi-phase (cumulative or stepwise) control measures in limiting impact of hazards acting upon supply from a specific aquaculture scenario. Where hazard impact can be mitigated by intervention (for example, biosecurity control plans, active monitoring, post-harvest processing and so on), either at single or multiple phases in supply, the SRT provides a basis to target measures most efficiently and to calculate ensuing benefits of intervention compared with the uncontrolled state. In situations where application of controls is unable to adequately limit the impact of specific hazards, the SRT may guide go/no-go decisions relating to the feasibility of a stated aquaculture scenario to fulfil its proposed consequences (that is, production of seafood for an intended market and use). Here, amendment of the scenario (for example, alternative farmed species, site, intended market and product use) may lead to improved outcomes where seafood can be safely produced and consumed (Fig. 1).

The SRT. In lieu of a single method to efficiently capture the combined impacts of diverse chemical and pathogen hazards on discrete phases of seafood supply, the SRT uses a two-step semi-quantitative risk assessment schema to calculate impact as a multiple of scores for severity of harm caused and the likelihood of harm occurring (Supplementary Section 2.2 and Supplementary Table 2.1). Application of the SRT requires initial definition of the aquaculture scenario under investigation, including data on specific taxonomy, geography, seasonality, production method, product type, proposed market and intended end use. Further, a supply phase-specific customized hazard list (within the hazard definitions of CH, AH and HH) should be tailored to the scenario and used as the basis for generation of impact scores via the SRT schema. Outputs from the SRT include cumulative impact scores for specific hazard categories acting through the whole supply chain and scores for specific hazards interacting at discrete phases of supply. The SRT can be applied to both 'uncontrolled' (no hazard mitigations applied) and 'controlled' (hazard mitigations applied) states to inform a biosecurity and seafood safety plan appropriate to the aquaculture scenario under investigation (Fig. 1).

Here we demonstrate application of the SRT to a hypothetical aquaculture scenario intending to produce farmed bivalve molluscs in coastal waters of a non-European Union (EU) marine state for intended live export (and raw consumption) within nations of the EU. The scenario was chosen to represent one in which multiple CH, AH and HH hazards are likely to interact with different phases in supply, and where recognized control measures are potentially available at state and sub-state levels to mitigate hazard impact. The filter-feeding behaviour of bivalve molluscs and propensity for some species groups (for example, oysters) to be consumed raw also represent a particularly good example of the intricate relationship between certain seafood types, hazards present in their growing environments and risk to human consumers of certain end products arising from the sector (Table 1 and Supplementary Section 2.3). Environmental pathogens (HH2), natural biological toxins (CH4), anthropogenic pathogens (HH2), heavy metals (CH1) and bacterial diseases (AH2) represented the top five cumulative uncontrolled risks over the whole supply chain (Fig. 2a). The top-ranking risks within each of these categories over the whole supply chain were *Vibrio parahaemolyticus* (in HH2); amnesic, paralytic and lipophilic biological toxins (in CH4); hepatitis A virus and *Salmonella* (in HH1); cadmium, mercury and lead (in CH1); and diseases caused by various *Vibrio* spp. (in AH2) (Fig. 2a and Supplementary Section 2.3). When specific supply phases were considered, pronounced impacts of AH hazards were predicted for early-life and grow-out phases (for example, viral, bacterial and parasite-induced mortality of animals on farms), with further potential for impact during the international trading phase, where pathogens of concern (for example, *Marteilia refringens*) are listed in legislation (Fig. 2b and Supplementary Section 2.3). Human health hazards had a less pronounced impact on production phases but presented a higher risk of impacting harvest and processing (for example, hepatitis A virus and norovirus), trading (for example, *Salmonella* spp. or high levels of indicator bacteria indicative of faecal contamination) and, particularly, consumption phases. In the latter, contamination by faecal-borne human pathogens such as hepatitis A virus, norovirus and *Vibrio cholerae* non-01/139 may elicit significant public health consequences via consumption, if not controlled (Fig. 2b and Supplementary Section 2.3). Similarly, CH had less impact on early-life and grow-out phases but impacted harvest and processing (for example, where concentrations of natural biological toxins exceed safe limits), trading (for example, where presence of heavy metals exceeds safe limits) and consumption phases (for example, where contamination of bivalves by natural biotoxins directly impacts human health) (Fig. 2b and Supplementary Section 2.3).

Application of the SRT to the uncontrolled state can directly support decisions to progress or amend the aquaculture scenario plan (Fig. 1). The uncontrolled SRT also provides a baseline to which a Risk Mitigation Matrix (RMM) can be applied—a bespoke inventory of measures aimed at reducing risk associated with specific hazards impacting discrete phases of supply. Figure 3 shows the application of the RMM to the bivalve mollusc scenario and compares SRT scores for the uncontrolled state in which no controls are applied with those where either standalone/non-accrued control measures are applied at discrete phases of supply (control 1) or where the benefit of controls applied at one phase are accrued in subsequent phases of supply (control 2) (details provided in Supplementary Section 2.3). For anthropogenically derived CH

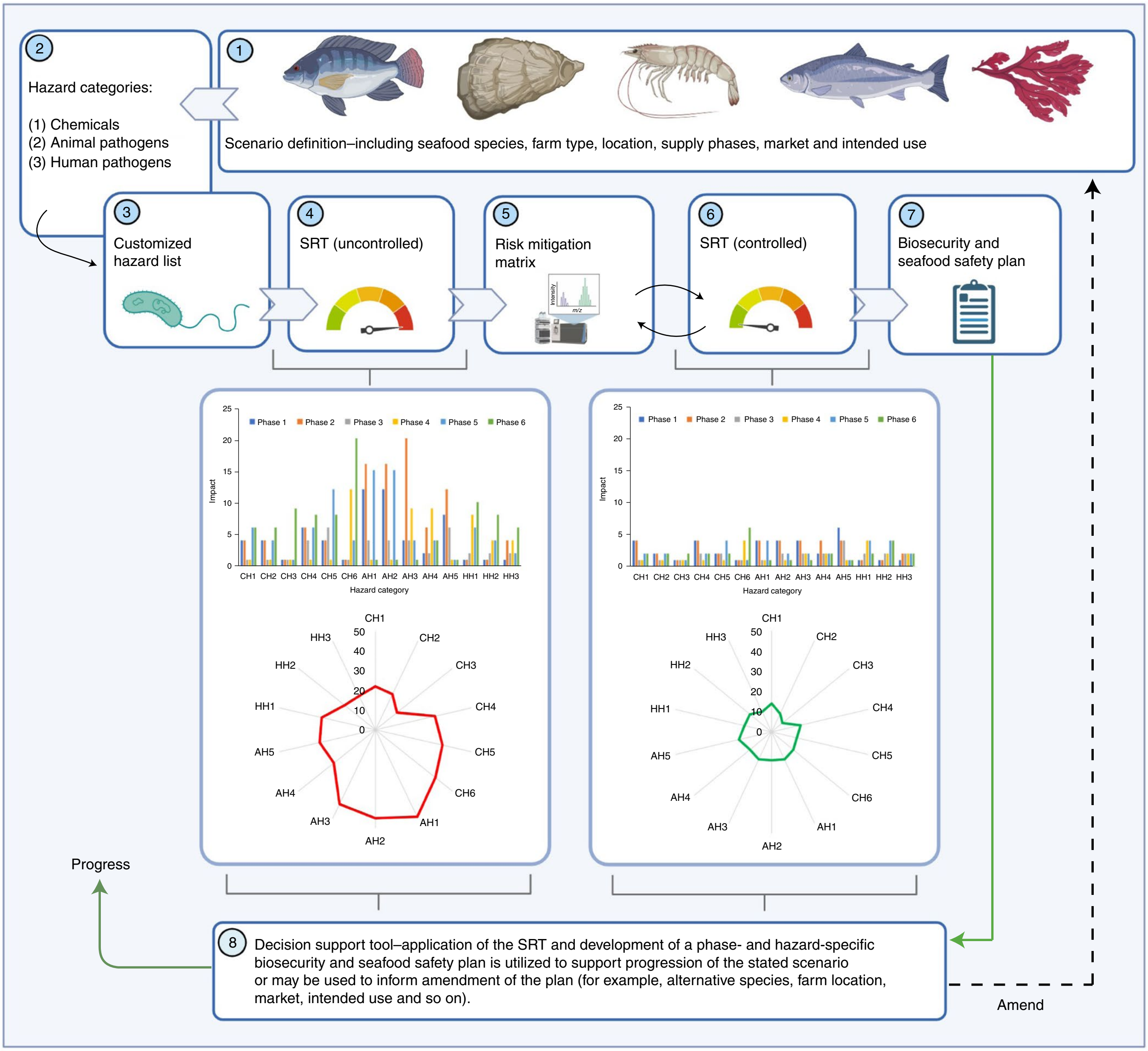

Fig. 1 | Application of the SRT to a specified aquaculture scenario. Stepwise progression requires a clear definition of the scenario to which the SRT is being applied (1) followed by the formation of a customized hazard list relating to the major CH, AH and HH hazard categories likely to interact with specific phases of supply (2 and 3). The SRT is initially applied to the uncontrolled state (4) where no mitigations are applied. By considering the role of phase-specific control options identified within the RMM (5), the SRT can be re-applied to this controlled state (6), repeating, if necessary, with different control combinations. The outturn is a biosecurity and seafood safety plan (7) that assists a decision to progress, amend or reject the aquaculture scenario in fulfilling its goal, as initially stated (8). CH1, heavy metals; CH2, persistent organic pollutants; CH3, radiological contaminants; CH4, natural biotoxins; CH5, veterinary, pharmaceutical and personal care chemicals; CH6, allergens; AH1, viral pathogens; AH2, bacterial pathogens; AH3, protistan pathogens; AH4, metazoan pathogens; AH5, syndromes; HH1, environmental pathogens; HH2, anthropogenically derived pathogens; HH3, zoonotic pathogens. See Table 1 for descriptions and examples of specific hazard types and their mode of interaction with seafood and Supplementary Section 2.1 for examples of hazard interaction with, and impact on, different seafood species groups. The spider diagram profiles represent the hypothetical risk profile when hazards are not controlled (red border) and when controls are applied (green border) throughout the supply chain for the scenario under consideration.

and HH hazards, benefits of controlling hazards through the supply chain are enhanced by siting of farms where comprehensive environmental characterization has already been performed[6,7]. Subsequently, interventions during harvest include suspension of harvest, transfer of live animals to cleaner sites ('relaying') or otherwise informing onward processing requirements. Processing interventions include purification through re-immersion in clean water (for example, depuration) or other mechanical interventions (for example, irradiation for denaturing potential human pathogens in final products)[8]. Further, product monitoring during the processing phase may either occur at the official services level and/or by the food business operator informed by the application of Hazard Analysis Critical Control Point (HACCP) plans (including batch release measures)[9]. Labelling and traceability, good hygiene

Table 1 | Hazard categories, types and examples of hazards (customized list) with the potential to interact with, and impact, the production, harvesting, processing, trade and safe consumption of animals destined for the seafood supply chain from aquaculture

Hazard category	Types	Example customized hazard list	Source, interaction with seafood and potential for impact
Chemicals	CH1: heavy metals	Cadmium, mercury, lead, zinc and copper	Wide-ranging natural or anthropogenic sources with potential to bioaccumulate and biomagnify in edible components of aquatic animals. Direct impact of heavy metals on survival, growth and development of (particularly) early life stages of wide-ranging aquatic animals[24]. Potential to impact human health via seafood consumption[25].
	CH2: persistent organic chemicals	Dioxins, furans, polychlorinated biphenyls, perfluorinated compounds, polybrominated diphenyl ethers, polycyclic aromatic hydrocarbons and wide-ranging emerging contaminants	Recalcitrant contaminants of aquatic environments and animals therein. Can bioaccumulate and biomagnify in seafood. Dioxins, furans and polychlorinated biphenyls readily absorbed via the human intestine and pass to infants via breastmilk[26]. Natural and anthropogenic polycyclic aromatic hydrocarbons are genotoxic, immunotoxic and carcinogenic[27]. Polybrominated compounds (for example, polybrominated diphenyl ethers) are neurotoxic and cause endocrine disruption[28]. Perfluorinated compounds invoke developmental toxicity[29]. Potential for additive 'mixture' effects of multiple persistent organic chemicals[30]. Seafood source location important when assessing risk of human exposure[31]. Indirect effects on growth, development and survival of aquatic animals likely.
	CH3: radiological contaminants	Radioactive isotopes, in particular strontium-90, caesium-137, plutonium isotopes and naturally occurring radioactive elements, such as radium-226 and polonium-210	Levels of radioactivity from anthropogenic and natural sources present in seafood are generally extremely low with no direct legislation prescribing safety limits. Instead, specific legislation is based on radiological risk assessments. Where nuclear accidents or emergencies occur, regional regulations may be enforced (for example, Council Regulation (Euratom) 2016/52). Legislation detailing maximum permitted levels of radionuclides in seafood activated, potentially accumulating in seafood and impacting trade[32]. Chronic radiation exposure (well above normal background levels) can impact reproduction and early life stages of aquatic animals[33].
	CH4: natural biotoxins	Paralytic shellfish poisoning, amnesic shellfish poisoning, diarrhetic shellfish poisoning, ciguatera, palytoxin and tetrodotoxin	Produced by certain microalgae and bacteria in freshwaters to open oceans. Phycotoxins (for example, paralytic shellfish poisoning) bioaccumulate in filter-feeding hosts and biomagnify through food webs. Acute risk to human consumers predominantly via consumption of contaminated molluscs—most phycotoxins are thermostable, resisting cooking[34]. Poisoning by other toxins (for example, ciguatoxin) linked to consumption of high-trophic-level carnivorous fish[35]. Emerging toxins (for example, tetrodotoxin) occurring in specific fish hosts cause human poisoning and have been more recently detected in wider-ranging aquatic hosts, including molluscs[36]. Some indirect effects of biotoxins on health of farmed fish stocks occur.
	CH5: veterinary, pharmaceutical and personal care chemicals	Antibiotics, ibuprofen, recreational drugs, sertraline, tamoxifen, salicylic acid and wide-ranging emerging contaminants	Veterinary medicines and other chemicals widely used (including illegally) in aquaculture to treat disease, as anaesthetics, and to manipulate physiology and immunity of stock. Residues can reside in edible components of seafood, with potential to impact human health[37]. Antibiotics use and misuse can drive emergence of antimicrobial resistant (AMR) microbes, some of which may impact health of seafood consumers[38]. Pharmaceutical and personal care chemicals enter waterways and accumulate in edible components of seafood[39]. Impacts are probably greatest where seafood arises from production in high-population-density urbanized waterways, including effects of human medicines and personal care chemicals on health of aquatic animals[40]. Complex mixture effects are likely, though understudied.
	CH6: allergens	Tropomyosin, troponin C, arginine kinase, β-parvalbumin, histamine and other natural allergens	Seafood allergy is a hypersensitivity disorder caused by numerous natural and spoilage-related elements present in fish and shellfish. Prevalence is increasing due to increasing seafood consumption, though misdiagnosis is frequent[41]. Common allergens are parvalbumin, tropomyosin and other proteins/peptides in fish and shellfish muscles. Histamine fish poisoning is a common seafood-borne disease associated with consumption of spoiled oily fish (for example, tuna) where muscle histidine is converted to histamine by bacterial histidine decarboxylase. Cooking destroys the bacteria but not the histamine[42]. Allergens are natural components of fish and shellfish tissues; thus, impacts are not associated with production phases of seafood.
Animal pathogens	AH1: viral pathogens	Tilapia Lake virus, white spot syndrome virus, oyster herpesvirus, infectious salmon anaemia virus, infectious pancreatic necrosis virus, pilchard orthomyxovirus and novel emergent pathogens	Taxonomically diverse DNA and RNA viral pathogens impacting health and survival of many wild and farmed seafood species. Originating in wildlife, viruses transmit efficiently within and between wild populations and captive stock, and emergence of novel pathogens is common. Viruses may be translocated between farms and regions as well as via global trade of live animals and fresh or frozen products, those with the greatest impact potentially becoming notifiable to the OIE[4]. Catastrophic production losses are reported in early-life and grow-out phases in aquaculture and in wild stocks. Viral pathogens reported in seafood species so far are not considered to be hazardous to human health. Novel technologies are revealing aquatic virus hyperdiversity, some of which may be linked to eventual emergence of pathogenic conditions in hosts.

Continued

Table 1 | Hazard categories, types and examples of hazards (customized list) with the potential to interact with, and impact, the production, harvesting, processing, trade and safe consumption of animals destined for the seafood supply chain from aquaculture (Continued)

Hazard category	Types	Example customized hazard list	Source, interaction with seafood and potential for impact
	AH2: bacterial pathogens	*Vibrio*, *Aeromonas*, *Flavobacterium*, *Pseudomonas*, *Streptococcus*, *Lactococcus*, *Mycobacterium*, obligate intracellular agents and novel emergent pathogens	Taxonomically diverse prokaryotic pathogens impacting health and survival of many wild and farmed seafood species. Include obligate pathogens and opportunistic agents causing disease in permissive scenarios. Translocation between farms, regions and nations reported. Potential for listing as notifiable diseases by OIE[4]. Single pathogen paradigms being augmented by studies on microbiomes/pathobiomes, including AMR strains[43]. Catastrophic production losses associated with early-life/grow-out phases and trade (in live animals/products where pathogen is listed). Some genera are considered zoonotic[44].
	AH3: protistan pathogens	*Bonamia* spp., *Enterocytozoon* spp., *Paramoeba* spp., *Ichthyophthirius* spp., *Kudoa* spp., *Hematodinium* spp. and novel emergent pathogens	Taxonomically diverse microbial eukaryotic organisms infecting tissue/organ/skin/blood systems of many wild and farmed seafood species. Epizootics reported in early-life and grow-out phases of production. Pathogens can drive mortality, cause product spoilage and affect trade. Lack of research on taxonomically obscure groups underlies frequent emergence of novel pathogens, even in commonly exploited hosts[45].
	AH4: metazoan pathogens	Platyhelminthes, cestodes, trematodes, nematodes, acanthocephalans and crustacean parasites	Taxonomically diverse metazoan eukaryotic organisms infecting many wild and farmed seafood species. Crustacean parasites cause significant direct losses in grow-out and during grading/harvest phases for salmon[46]. Platyhelminthes impact grow-out and trading of salmonids and are listed by OIE owing to potential for impact on wild stocks[4]. Nematode, trematode and cestode infestations cause pathology in invertebrate and fish hosts. Pathology is usually limited but can cause marketing issues for products—some have zoonotic potential (covered under hazard category HH3).
	AH5: syndromes	Red mark syndrome, proliferative gill inflammation, white faeces syndrome, epizootic shell disease and various pathobiome disorders	Syndromes are groupings of clinical signs associated with a particular health condition but for which specific aetiology has not been elucidated. Often associated with disorders in major organ systems, including skin, gills, carapace and gut. Emerging molecular diagnostic tools are augmenting pathology studies to identify cryptic pathogens or multi-agent dysbioses[47]. Development of syndromes may be driven by influence of wider stressors (including climate, feed quality, host genetics, exposure to chemicals and so on). Increased focus is required due to their impact on yield in numerous aquaculture sectors.
Human pathogens	HH1: environmental pathogens	Members of genus *Vibrio*, including *V. vulnificus*, *V. parahaemolyticus* and *V. cholerae*	Autochthonous constituents of aquatic environments, often favouring warm/brackish conditions. Responsible for human illness associated with seafood contact and consumption, particularly of filter-feeding molluscs. Clinical manifestations range from mild-to-severe gastroenteritis to primary septicaemia and death (the latter from wounding following contact with contaminated shellfish)[48]. Vibrios are acknowledged as important sources of seafood-associated illness, but global surveillance is lacking. Climate change offers opportunities for further emergence and potential pandemic spread[49]. While main effects occur in the consumption phase, some taxa (for example, *V. parahaemolyticus*) are important aquatic animal pathogens affecting early-life and grow-out phases (see hazard category AH2).
	HH2: anthropogenically derived pathogens	Enteric viruses (norovirus, poliovirus and hepatitis A and E), bacteria (for example, *Salmonella enterica*, *Escherichia coli* and *Campylobacter jejuni*) and parasites (for example, *Giardia*, *Crytptosporidium* and *Enterocytozoon*)	Originating from human, animal or industrial sources that contaminate waterways via wastewater and run-off. Cause food-borne illness via consumption of seafood. Numerous viral, bacterial and parasite taxa detected in freshwater and marine seafood destined for human consumption (for example, *Salmonella*[50]). Contamination in harvest (including processing, handling and storage) via human-driven contamination. Food-borne pathogens impact trade and consumption phases, with bivalve molluscs being the most common source of consumer illness, particularly where products are eaten raw[51]. Food-borne pathogens do not have a significant direct impact on the health of aquatic animals during production phases.
	HH3: zoonotic pathogens	*Anasakis* spp., *Paragonimus* spp., *Mycobacterium* spp., *Streptococcus agalactiae*, *Diphyllobothrium* spp. and AMR agents	Aquatic animal pathogens able to be transmitted to cause infection in humans. Include direct infection by bacterial pathogens via contact/consumption, parasites where humans act as reservoir, paratenic or definite hosts (for example, *Paragonimus*[52]) and AMR agents associated with seafood that may be transmitted to humans via contact/consumption (for example, *Streptococcus*[53]). Zoonotic parasite transmission generally associated with consumption of raw/undercooked seafood, causing gastro-intestinal complications or more systemic infection. Aquatic zoonoses are probably under-reported, with the occurrence of emerging pathogens increasing as contact between aquatic animals and people increases.

Detailed descriptions of example interactions with marine fish, freshwater fish, crustaceans and molluscs are provided in Supplementary Section 2.1

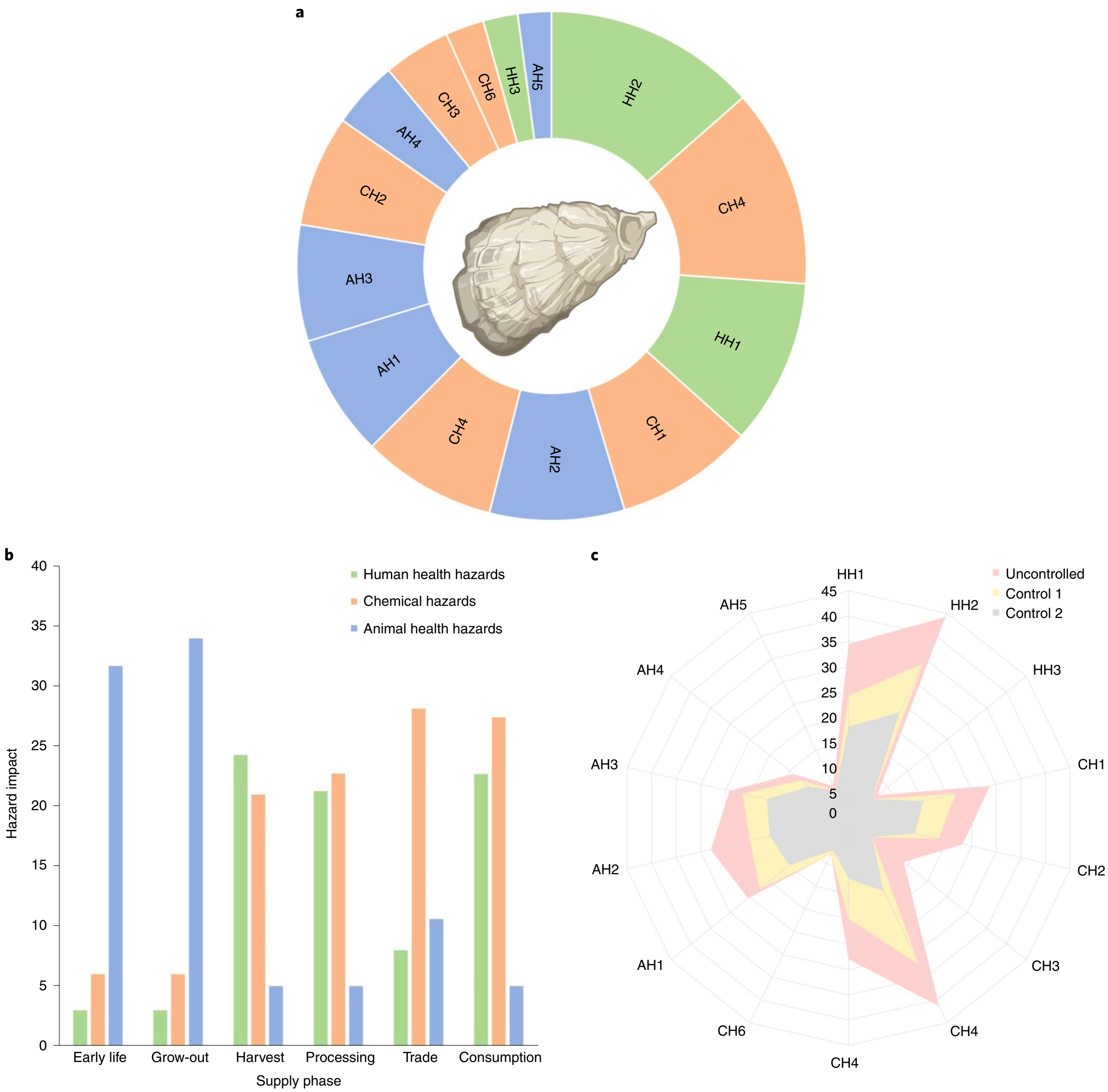

Fig. 2 | Application of the SRT to a bivalve mollusc aquaculture scenario in which live animals are destined for an export market for consumption in raw form. a, Cumulative SRT scores for uncontrolled impact of 14 hazard types across all phases in supply. The top five relative cumulative risks are associated with impact of HH2 (anthropogenically derived pathogens), CH4 (natural biotoxins), HH1 (environmental pathogens), CH1 (heavy metals) and AH2 (bacterial pathogens). **b**, Relative impact of hazards belonging to hazard categories CH, AH and HH at the six phases in supply; animal health hazards impact predominantly during production phases (and during trade) while human health and chemical hazards impact more greatly during harvest and post-harvest phases. **c**, Hazard-specific relative impact following application of control measures as detailed in the RMM for bivalve molluscs (Fig. 3). Control 1 (non-accrued scores) and control 2 (accrued scores) are compared with the uncontrolled state in which no phase-specific controls are applied. See Table 1 for descriptions and examples of specific hazard types and their mode of interaction with seafood and Supplementary Section 2.1 for examples of hazard interaction with, and impact on, different seafood species groups.

practices, general education of workers (such as cold chain breaches and contamination by staff with diarrhoea–vomiting symptoms) and avoidance of consumption of raw product by ‘at risk’ groups are critical measures for reducing risk during the consumption phase[10].

For AH hazards, interventions during the production phase may be essential, including initiatives such as the Progressive Management Pathway for Aquatic Biosecurity approach supported by appropriate national biosecurity tools[11], on-farm biosecurity planning

	Early life	Grow-out	Harvest	Processing	Trade	Consumption	Uncontrolled	Control 1	Control 2
CH1	NA[a]	NA[a]	Initial site selection (based on risk assessment), site-catchment level monitoring and action post monitoring[b]	Product-level monitoring (food safety criteria)[d]	Regional/national legislation (EU, Codex)	NA	28.72	21.76	15.24
CH2	NA[a]	NA[a]	Initial site selection (based on risk assessment), site-catchment level monitoring and action post monitoring[b]	Product-level monitoring (food safety criteria)[d]	Regional/national legislation (EU, Codex)	NA	23.2	18.28	13.52
CH3	NA[a]	NA[a]	Initial site selection (based on risk assessment), site-catchment level monitoring and action post monitoring[b]	Product-level monitoring (food safety criteria)[d]	Regional/national legislation (EU, Codex)	NA	14	6	6
CH4	NA[a]	NA[a]	Initial site selection (based on risk assessment), site-catchment level monitoring and action post monitoring[b]	Product-level monitoring (food safety criteria)[d]	Regional/national legislation (EU, Codex)	NA	41.38	32.19	16.07
CH5	NA[a]	NA[a]	Initial site selection (based on risk assessment), site-catchment level monitoring and action post monitoring[b]	Product-level monitoring (food safety criteria)[d]	Regional/national legislation (EU, Codex)	NA	28	20	12
CH6	NA	NA	NA	Product-level monitoring (food safety criteria)[d]	Regional/national legislation (EU, Codex)	NA	8	8	7
AH1	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	NA	OIE (international) and/or regional and national controls[g]	NA	25.5	22.5	15
AH2	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	OIE Code, PMP-AB, on-farm biosecurity and BAP[6]	NA	OIE (international) and/or regional and national controls[g]	NA	28	20	16
AH3	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	NA	OIE (international) and/or regional and national controls[g]	NA	24.18	21.55	16.65
AH4	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	NA	Regional and national controls[g]	NA	14	12	10
AH5	PMP-AB, on-farm biosecurity and BAP[f]	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	OIE Code, PMP-AB, on-farm biosecurity and BAP[f]	NA	Regional and national controls[g]	NA	7	6	6
HH1	NA[a]	NA[a]	Initial site selection (based on risk assessment), site-catchment level monitoring and action post monitoring[b]	Application of food safety or process hygiene criteria[c]	Regional/national legislation (EU, Codex)	Cold chain measures, good hygienic practice, education at point of sale (consumers, staff) and product labelling[e]	34.5	24.25	18.13
HH2	NA[a]	NA[a]	Initial site selection (based on risk assessment), site-catchment level monitoring and action post monitoring[b]	Application of food safety or process hygiene criteria[c]	Regional/national legislation (EU, Codex)	Cold chain measures, good hygienic practice and education at point of sale (consumers, staff) product labelling[e]	44.25	33.99	23.26
HH3	NA[a]	NA[a]	Initial site selection (based on risk assessment), site-catchment level monitoring and action post monitoring[b]	Application of food safety or process hygiene criteria[c]	Regional/national legislation (EU, Codex)	Cold chain measures, good hygienic practice and education at point of sale (consumers, staff) product labelling[e]	7.22	6	6

Fig. 3 | RMM applied to bivalve mollusc aquaculture scenario where live animals are destined for export market to be consumed raw. Control measures for specific hazards can be applied to given supply phases. The RMM informs re-application of the SRT to the uncontrolled scenario (no mitigations applied) for potential de-risking of supply using standalone/non-accrued benefits of applying controls at specific supply phases supply (control 1) or to cumulative/accrued benefits of applying controls at subsequent supply phases (control 2). Resultant scores are represented in red, yellow and grey columns (Fig. 2c). Data relating to calculation of the SRT for these control options are provided in Supplementary Section 2.3. [a]Site pre-selection (covering CH, AH and HH hazards) offers the best risk mitigation measure that may be accrued during all subsequent supply phases. [b]Actions include suspension of harvest, 'relaying' animals at clean sites or otherwise informing onward processing requirements. [c]Purification through re-immersion of molluscs in clean water (for example, depuration and relay) or other mechanical interventions where criteria for efficacy of intervention are measurable (for example, irradiation). [d]Product monitoring either by official services or food businesses informed by application of HACCP plans (including batch release measures). [e]Good hygiene practices and education of workers to avoid cold chain breach, contamination of seafood by staff and consumption by 'at risk' groups; labelling and traceability are critical. [f]Application of Progressive Management Pathway, supported by appropriate national biosecurity tools, on-farm biosecurity plans, application of BAP or similar, application of measures in OIE Code for listed pathogens and generic chapters (surveillance and biosecurity) for other pathogens. [g]Application of OIE standards for international trade as recognized by the WTO, including more stringent national/regional controls where justified by risk assessment, and meeting other criteria (equivalence) set out in the WTO SPS agreement. NA, not applicable.

(determined by government biosecurity policy/practice) and application of best aquaculture practices (BAP) approaches from organizations such as the Global Aquaculture Alliance[12]. During the trading phase, application of the Office International des Epizooties (OIE) Code is relevant for listed pathogens, with generic chapters (surveillance and biosecurity) also contributing to de-risking of disease outbreaks from non-listed taxa. Most producer and trading countries are OIE members, with standards for international trade recognized by the World Trade Organization (WTO). More stringent national/regional controls can also be implemented if justified by risk assessment and meeting other criteria (equivalence) set out in the WTO SPS (sanitary and phytosanitary measures) agreement[13]. For the bivalve mollusc scenario, benefits of application of control measures are set out in Fig. 3 and summarized in Fig. 2c (detailed in Supplementary Sections 2.1 and 2.3). The most pronounced reductions in risk were observed where controls were applied in early phases, and accrued at subsequent phases, of supply. For some hazards (for example, CH6), the application of available controls did not materially reduce risk; for CH6 hazards, avoidance of a product by susceptible consumer groups was the most relevant measure to reduce risk (Supplementary Section 2.3). The SRT is widely applicable to other aquaculture scenarios, including for marine fish, freshwater fish and crustaceans, using the schema presented here—although in each scenario, the impacts of hazards associated with discrete CH, AH and HH hazards acting at specific phases in supply are expected to differ significantly (Supplementary Section 2.1).

Policy implications and outlook. Diverse hazards interacting with seafood supply undermine sustainability via lost yield (food and profit) relative to the human, organism and environmental capital inputs required to create it[2]. Aquatic animal health and seafood safety are public goods, given that they cannot be easily purchased in the marketplace and thus require government intervention to ensure they are enacted[9,14]. Nationally, state-level responsible authorities designated to oversee aquaculture production and trade must be supported by official control laboratories able to apply quality-assured surveillance, analytical and diagnostic tools with respect to animal health (for example, OIE, the Progressive Management Pathway for Aquaculture Biosecurity (PMP-AB) and National Biosecurity Plan), anthropogenic and natural contaminants, and pathogens threatening seafood safety (for example, Codex Alimentarius codes of practice and standards). Known hazards (where regulatory requirements exist) can also be controlled by industry (for example, by farm-level best management practice and application of HACCPs to production and processing), supported by formal responsible authority monitoring, and surveillance activities and audit functions. Individual and societal preferences for, say, cooked seafood may confer additional protection against the impact of microbial hazards present within some seafoods, though they may have less effect at mitigating the risk of chemical threats. Where seafood is exported, regulations spanning primary production and final product are frequently in force with audit by importing countries or by trading blocs (for example, the EU) helping to mitigate risks of identified hazards in final products for consumers within those markets. The desire to trade often becomes a primary motive for deployment of hazard controls in producer nations. However, understanding hazards at each stage of the supply chain in the country or region of production, which may vary geographically, is considered vital irrespective of whether the product is destined for export or domestic markets. For all seafood production, quality and safety standards should be designed to control risks extant within that region and intended use of the product, with export regulatory requirements applied in addition.

Increased reliance on protein arising from aquaculture in global diets[3] coupled with significant potential for blue foods to support development of a 'low stressor' global food system[15] must now be placed in context with the impact of mass global human migrations to coastal zones[16], substantial pressures on water supply and quality, and the widespread use of water systems to dispose of human, agricultural and industrial wastes containing diverse pollutants[17]. Special focus must be applied to low- and middle-income nations where >90% of current aquaculture production occurs, where the most future growth and altered blue food consumption is predicted[3] and where the majority of wastewater from land-based sources is currently discharged without treatment[17]. While predominant scientific, policy and public discourse has focused on the potential impact of aquaculture on aquatic systems—outlined and discussed in ref. [2]—much less consideration has been paid to the impact of land-based human activities on contamination of those aquatic habitats that will be increasingly relied upon to provide human dietary protein in the coming decades[18]. The SRT considers those hazards with potential for greatest impact on supply of seafood from different aquaculture sectors, and the transnational-, state-, farm- and societal-level interventions that may be required to mitigate them. It also provides a flexible framework to which novel emerging chemical and pathogen hazards may be added, potentially including those hazards (exemplified by severe acute respiratory syndrome coronavirus 2) that although not directly impacting aquatic animal health or seafood safety may nevertheless significantly impact supply chains[19]. For enactment, national strategies for aquaculture growth must therefore include (or interact with) comprehensive policies aimed at protecting aquatic habitats from diverse pollution sources, not least to protect the biodiversity upon which future aquaculture and its diversification will inevitably rely[19]. Initiatives such as the Global Burden of Animal Diseases approach aimed at identifying baseline metrics for supply chain losses (to disease) and justifying resource allocation for interventions may provide a logical methodology for extension to justify investment in the control of wider chemical and microbial hazards in food systems[20]. Further, proportional investment in state infrastructures that minimize the release of hazards to aquatic systems and increase the capability to detect known and emerging hazards where they occur and to apply appropriate controls to ensure the blue food revolution is a safe one should be considered a multi-faceted public good, where benefits extend beyond food and wealth to protection of biodiversity and climate change mitigation relative to food systems.

Methods

The SRT scores were generated for farmed bivalve molluscs in coastal waters of a non-EU marine state for live export (and raw consumption) within nations of the EU through small expert group elicitation (subgroups of authors of this paper) for each hazard category or subcategory, according to the framework provided in Fig. 1 (and detailed in Supplementary Sections 2.2 and 2.3). Impact and likelihood scores (with supporting evidence) for discrete hazard categories acting at specific phases in the supply chain for bivalve molluscs were provided by each subgroup to a coordinator (R.H.). The coordinator (an expert in the scenario under consideration), working with representatives of each subgroup, then agreed a final score for each hazard (at each phase) on the basis of evidence presented, using a probabilistic approach. Subgroups were asked to assess three states: (1) where there is uncontrolled impact of hazards on supply; (2) where application of phase-specific control measures is used to limit impact on supply; (3) where application of multi-phase (cumulative or stepwise) control measures is used to limit impact on supply. The evidence used was a mixture of peer review, grey literature and expert opinion generated within subgroups and was represented as the RMM provided in Fig. 3. The semi-quantitative process broadly followed the expert knowledge elicitation method, a structured approach to collate opinions from expert groups in a transparent manner focusing primarily on probabilistic methods to elicit expert judgement on quantitative parameters whilst minimizing bias[21]. Other formal expert elicitation processes (for example, the IDEA protocol)[22] have previously been used to calculate impact of discrete aquatic animal diseases in aquaculture[23] and may also be suitable to SRT application.

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Author contributions

G.D.S., R.E.H. and E.J.P. conceptualized the approach presented in this paper. In particular, the SRT, broadened to include wide-ranging chemical and pathogen hazards, was inspired by approaches described in 'Technical guidance for the development of the growing area aspects of Bivalve Mollusc Sanitation Programmes' published by the Food and Agriculture Organization and the World Health Organization (https://www.fao.org/documents/card/en/c/ca1213en/). These and all other authors contributed to the generation of hazard categories and types as well as the formation of the customized hazard list to which the SRT was applied. In addition, subgroups of authors contributed to the application of the SRT to the bivalve mollusc scenario and identification of potential controls outlined in the RMM.

Competing interests

The authors declare no competing interests.

Additional information

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