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Marine diseases as a threat to society: Adopting and advancing the UNDRR risk framework

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ABSTRACT

Marine diseases change ecosystem dynamics and functioning, and modify ecosystem service (e.g. food) provisioning. Understanding marine diseases' occurrence and frequency, and consequences and impacts thereof, is crucial for humans and nature alike, though the implications for society beyond human health have received little attention in scientific debates yet. This study advocates for the uptake of marine diseases into hazard landscapes currently being evaluated and discusses the different components of risks that marine diseases pose to societies: Adopting the analytical lens of the UNDRR risk framework to oyster farms as a specific case, we explore disease outbreaks in those as hazards to society. Looking at associated exposure and vulnerability, potential risk reduction options are elaborated. The framework is broadened by including indirect and spill-over effects within the social-ecological system – to local coastal communities. Marine diseases management is challenged by the fluidity of the ocean and fragmented governance structures. To reduce social-ecological repercussions and overall risks for society of disease outbreaks we thus endorse for a thorough risk evaluation and sensible, anticipatory communication.

1. Introduction and rationale

The recent COVID-19 pandemic has shown in an impressive way how diverse and far-reaching – yet somewhat unpredictable – the effects of a disease outbreak can trickle through society: Not only have many humans suffered from direct health effects, but almost all economic sectors experienced drastic consequences of pandemic-induced restrictions and adaptation measures (e.g. lockdowns, mobility restrictions, …). And while not all diseases may carry the potential for creating a 'tsunami' of such magnitude, the risk of disease events for society became clear. The uncertainty in timing and scale of disease occurrence and effects requires urgent and proactive risk evaluation and management.

Marine-borne disease outbreaks present unique challenges due to the fluid nature of our ocean, diverse(r) contagion pathways (when compared to land-based diseases) and the uncertainty related to the scale of their impact. These provide ground to legitimate concerns linked to marine disease occurrences and perpetuating consequences, in particular when marine diseases bridge the water-land divide and when marine resources are part of transmission pathways that are exploited by humans, for example via seafood consumption.

Addressing current and future (coastal) risks requires urgent action to mitigate the impacts from coastal hazards and boost the resilience of coastal communities (Ruckelshaus et al., 2020) and this is why managing coastal risk and response to disasters is a national priority for many nations (UNISDR - United Nations Office for Disaster Risk Reduction, 2017). Today's hazard landscape is diverse and frameworks for structured risks assessments such as the one of the UNDRR (United Nations Office for Disaster Risk Reduction) of hazardous events are available and in use. However, they have so far not been applied to risks for society emerging from marine diseases. We argue that considering marine diseases as part of hazard landscapes to be evaluated by the UNDRR framework allows to advance holistic risk assessments for coast and society. This work thus addresses this gap by adopting the UNDRR

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risk framework to marine diseases, while advancing it via the inclusion of spill-over effects for (local) society. We use diseases affecting oyster cultures as an example to discuss risks as a product of hazard (oyster pathogen), exposure and vulnerability (to the hazard), as well as risk reduction options for all determinants of risk. By taking a step back, elaborating an overview perspective, the application of such frameworks aims to support transparent and conclusive risk communication and clearly structured advice how to avoid and/or minimize risk. Overall, we contribute in three ways to the current scientific discourse: First, we consider marine disease in a risk framework to discuss suitable governance options. Second, we present a version of the known UNDRR risk framework adapted to social-ecological systems (SES) that explicitly accounts for the different services provided by an ecosystem. Third, we apply this framework to the case of oyster aquaculture as an example of its analytical strengths/utility, but also to help translating the theoretical contribution into actionable strategies for risk reduction management.

2. Context: marine diseases and their potential societal impacts

Human action may directly (e.g. habitat destruction) or indirectly (e.g. climate change effects) drive marine disease occurrence. On the other hand, marine diseases (i.e. infections with bacteria, parasites, viruses, etc.) emerging from natural processes within ecosystems but also from unregulated or excessive human activity both in the ocean and on land, can also represent a risk to society. For example, a hazardous disease event may negatively affect marine resources target of fisheries and aquaculture, water quality, biodiversity dynamics and ecosystem integrity and the provisioning of (other) ecosystem services such as recreational value – which may result in drastic consequences for human health, food security and livelihoods (e.g. Burge et al., 2014; Lafferty and Hofmann, 2016).

Not all marine disease present immediate threats that can escalate into significant risks to society: Parasites and pathogens are common in all hosts from algae to fish (Poulin and Morand, 2000; Groner et al., 2016; del Campo et al., 2020) and marine diseases only become a concern when substantial ecological, economic or social impacts occur (Groner et al., 2016). So far, research remained mostly focused on ecological impacts (e.g. Porter, 2013; Coen and Bishop, 2015; Guo and Ford, 2016) and to a lesser degree on economic or social effects (e.g. Lafferty et al., 2015; Froelich and Noble, 2016; Behringer et al., 2020; Afewerki et al., 2023). Especially the impact on society has found little attention in recent debates on ocean health (e.g. Legat et al., 2016; Koesling et al., *under review*), and only a few examples of large-scale wildlife management programs exist that address marine diseases (Glidden et al., 2022). Effective disease management is rendered difficult by general fundamental differences between marine and terrestrial systems (Glidden et al., 2022). Disease outbreaks in the marine realm are extremely complex and multifactorial, and drivers of marine diseases are still to be completely understood, and how these perpetuate with human action and affect society (i.e. unclear "disease aetiology", Hudson and Egan, 2024). This lack of knowledge, combined with missing diagnostic tools, and treatment and mitigation options (Hudson and Egan, 2024) likely explains why current policies often do not cover marine disease outbreaks as emergencies (Groner et al., 2016). This results in high uncertainties involved in predicting disease outbreaks – and effects thereof. This work aims to close the gap related to suitable frameworks to discuss the role of marine diseases for society and its governance, and illustrate how the UNDRR risk framework can be applied in the context of marine diseases.

3. Challenge framing: how to capture risk?

Climate change can be a driver for marine diseases (Ward and Lafferty, 2004; Burge et al., 2014; Rowley et al., 2014; Hernroth and Baden, 2018; Burge and Hershberger, 2020) and environmental hazards such as eutrophication alter disease dynamics (Johnson et al., 2008); and marine diseases themselves potentially cause repercussions for the environment. Yet outbreaks of marine diseases are surrounded by uncertainties. The Intergovernmental Panel on Climate Change (IPCC) first discussed the determinants of risk (emerging from climate-related impacts) as hazard, vulnerability and exposure (IPCC 2014a, 2014b). Simpson et al. (2021) and later IPCC reports (IPCC, 2022) included the discussion of interactions among "multiple drivers of climate change risk" (including adaptation and mitigation responses). The IPCC risk vocabulary was also taken up by the UN's Sendai Framework for Disaster Risk Reduction (UNISDR, 2015), which articulates the need for improved understanding of disaster risk in all its dimensions (hazard, exposure, vulnerability) and the strengthening of disaster risk governance. So far, these discussions and frameworks focused on climate change (IPCC) and natural disasters (Sendai).

Our interdisciplinary group of researchers herein interprets risk (R) as a product of hazard (H), exposure (E) and vulnerability (V) (R = H x E x V) (Fig. 1). As such, the risk of a marine disease is the risk a particular species (group) faces to experience a hazardous event (the disease outbreak), and one can then disentangle exposure and vulnerability to the hazard (the pathogen). We thereafter apply our complementary disciplinary research expertise and perspectives to the different risk domains to discuss and articulate risk reduction options in the determinants exposure and vulnerability as to decrease the likelihood of occurrence of a hazardous event (Fig. 1).

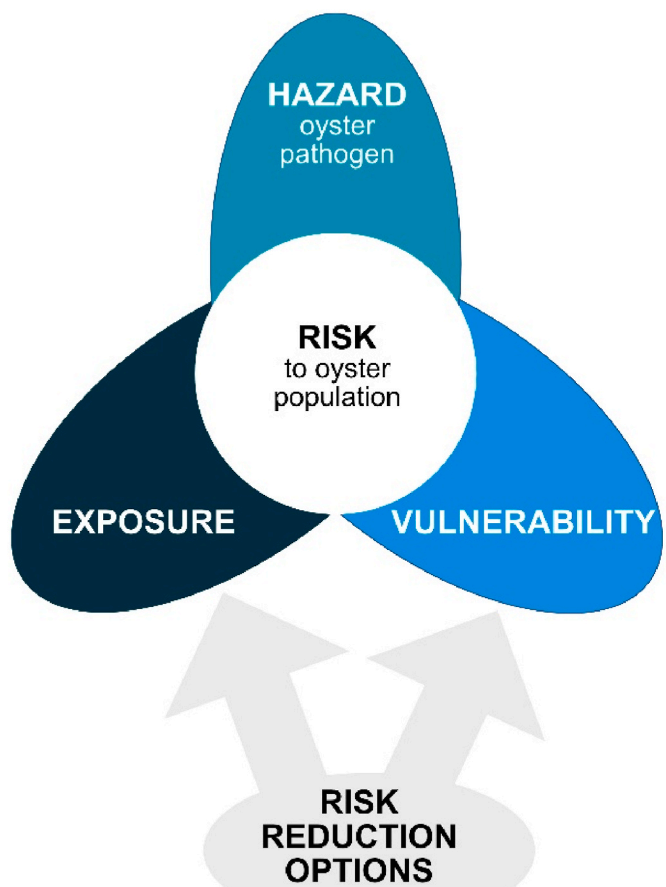

Fig. 1. Our framework to assess risks associated with marine diseases, following the UNDRR risk framework (UNDRR = United Nations Office for Disaster Risk Reduction; UNISDR, 2015) conceptualizing risk (here: the risk for oyster population to experience a hazardous event, i.e. a marine disease outbreak) as a product of hazard (oyster pathogen), exposure and vulnerability (to the hazard); to then discuss risk reduction options in all dimensions as a fourth dimension. Figure modified after Figure SPM.1 in IPCC (2014a).

4. Solution proposition: the adaptation of the sendai risk framework

We started our analysis with two types of literature reviews: first to clarify the concept of marine diseases and then to examine scientific debates surrounding our case study (for methodological details see Appendix 1). Next, we adapted the existing Sendai risk framework to the case of social-economic systems by a) including the concept of ecosystem services based on the CICES framework (CICES = Common International Classification of Ecosystem Services; Haines-Young and Potschin-Young, 2018) and b) advocating for an anticipatory risk management strategy: elaborating risk reduction options for within the risks determinants exposure and vulnerability as to decrease the likelihood of occurrence of a hazardous event (instead of retroactive responses as do, e.g. Simpson et al., 2021). The CICES lens is herein used as a structuring element for the evaluation of spill-over effects to local societies, i.e. for the discussion of how marine disease outbreaks present a hazard to coastal societies (see section 5.2.1). Throughout, we apply this adapted framework to farmed oysters (*Crassostrea/Magallana* spp.*, Ostrea* spp.*, Saccostrea* spp., cf. Table 1) as a case study for marine diseases by detailing risk reduction options in all risk domains (Table 2). For a detailed overview of the methodological approach see Appendix 1.

From a financial standpoint, the costliest marine epidemics are those affecting commercial species – like oysters. The most common route for humans to get infected with marine diseases is through the dietary intake of seafood (Groner et al., 2016). Besides their significant role in seafood provisioning, oyster culture – in contrast to fish and shrimp farming – does not rely on any feed input. Beyond that, they are important ecosystem engineers (e.g. creating habitat for other organisms, *sensu* Jones et al., 1994, 1997) and sentinels, and shape ecosystem dynamics via their filtration activity. Marine epidemics that disrupt the oysters' role in ecosystem dynamics can thus significantly impact human societies beyond what is typically considered, i.e. food provisioning. Finally, oysters are the best-studied marine bivalve host of infectious diseases (Burge et al., 2014). This all makes marine diseases in oyster cultures a highly suitable case study to apply and illustrate the workflow of the adapted UNDRR risk framework and to demonstrate how such frameworks may adopt a social-ecological perspective for assessing impacts and response options for society. Reasons for using a standardized risk framework are manyfold, including time and resource efficiency as well as quality and transparency improvement; and the potential for a quicker adoption of management actions to reduce future risk. This approach invites for being replicated and further adopted to other species and/or diseases.

According to UNISDR (2015) a *hazard* is "a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation". A *hazardous event* is the manifestation (occurrence) of a hazard in a particular place during a particular period of time. When discussing marine diseases, a disease agent (e.g. viruses, bacteria, protists, metazoans) represents the initial hazard for the ecological subsystem of the SES. *Exposure* characterizes the current situation or setting of infrastructure, production capacities, people and other tangible human assets located in hazard-prone areas (UNISDR, 2015). The concept of *vulnerability* was introduced in the Disaster Risk Reduction and Climate Change Adaptation communities to better understand the diverging adverse effects of hazards or climate change impacts on different societies or subgroups thereof. Both communities agree that risk is not driven by physical events outside human control but primarily by exposure and vulnerability to those events (Birkmann and McMillan, 2020). Vulnerability is defined as "[t]he conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" (UNDRR, 2016, p. 24) and "[t]he propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC et al., 2019). This means that we conceptualize the pathogen occurrence as the initial hazard, to then discuss the risk (a composite result of hazard, exposure and vulnerability) to oyster population, representing the core of the SES' ecological subsystem.

But: marine diseases do not only affect ecosystems, but also societies interacting with and depending on nature – they unfold within complex SES. This is why we decided to disentangle the multiple layers on which a hazardous event (the oyster disease outbreak) may affect and perpetuate on, acknowledging that a disease outbreak in the ecological subsystem may have cascading effects on the social system (Fig. 2). Thus, and following the definitions of a hazard above, a disease outbreak in an oyster culture in a particular year and location is a hazardous event for which the risk to (coastal) society has to be evaluated in a second step (Fig. 2). This means that once a disaster occurs (i.e. the hazardous event unfolds) in the ecological subsystem, the risk of such an event to the local society can be evaluated – by discussing hazard (disease occurrence), exposure and vulnerability on this second level. The consideration of such spill-over effects represents a clear novelty of the adapted framework presented herein.

5. Solution demonstration: applying our adapted risk framework to marine disease outbreaks in oyster cultures

The hazard pathogen occurrence, and exposure and vulnerability thereto, are described in section 5.1 and Table 1. Once the hazardous event (disease outbreak) unfolds in the ecological realm, the resulting risk of disease occurrence – and exposure and vulnerability thereto – to the local society can be evaluated (Section 5.2). Further cascading (e.g. to national society) and feedback loops may evolve and could be evaluated in subsequent further steps, but was not focus of the present work. For both levels (pathogen occurrence, oyster disease occurrence), and the composite dimensions of associated risk(s), risk reduction options need to be elaborated (Section 5.3, Table 2).

5.1. The risk of disease outbreaks in oyster population

5.1.1. Pathogens as hazards to oyster populations

Our literature review revealed that the terminology of "marine diseases" includes a variety of dimensions: different disease agents may affect different (components of) hosts, which may (or not) result in a disease outbreak (the hazardous event) and may have (if at all) differential (and context-specific) effects for the ecosystem and/or society (see section 5.2). Important for the normative discussion of marine diseases as hazards is further the fact that many disease names are not explicitly specified in the literature. Rather, many authors discuss the pathogen itself, because the resulting symptoms of the disease are more difficult to capture and conceptualize. And in fact, though oysters may be hosts to different pathogenic viruses, bacteria, and protists, causing a range of different diseases (Table 1) in bivalves (and thus oysters), the term "infection with pathogenic agent" is typically preferred over describing the disease itself. Oyster mortality is mainly used as an indicator for identifying problematic situations, and not the symptoms. We believe that this perspective makes sense as the (massive) die-off of oysters in a particular aquaculture will affect significantly the surrounding ecosystem and humans through the alteration of ecosystem service provisioning (and hence represent a hazard to local society; see section 5.2.1).

5.1.2. Exposure of different culture systems to oyster disease pathogens

The exposure to the pathogen occurrence will depend on its position against physical-environmental and pathogen (disease) dynamics, as well as human action (Le Groumellec et al. 2008). Exposure of oyster culture systems will differ *inter alia* depending on general environmental conditions, the location and culture system used, but some generalities can be derived.

Table 1
Marine diseases as hazards: Overview (non-exhaustive) of different agents causing a broad range of diseases affecting oysters (based on Laffery (2017), who expanded this from Lafferty et al. (2015), and complemented by own knowledge) and a selection of publications describing agent and the oyster disease, respectively (identified as part of the present work). Information related to species other than *Crassostrea/Magallana* spp. are in grey.

Disease agent	Disease host (oyster species showing mortality and/or lesions when infected)	Associated disease(s)	Publications on the disease agent (first characterizations of agent)	Examples of publications on the disease itself (description of mortality and/or lesions)
Viruses				
Irido-like virus	*Magallana angulata* *Magallana gigas*	Gill Disease of Portuguese Oyster; Gill necrosis virus disease (GNV); Haemocytic infection virus disease (HIV); Oyster velar virus disease (OVVD); Blister disease.	Comps et al. (1976); Elston (1979)	Alderman and Gras (1969); Elston and Wilkinson (1985); Arzul et al. (2017)
Ostreid herpesvirus 1 (incl. microvariants)	*Magallana gigas* *Magallana angulate*	Herpes-type virus disease (in Australia, also Pacific Oyster Mortality Syndrom, POMS)	Nicolas et al. (1992); Le Deuff and Renault (1999); Segarra et al. (2010); Jenkins et al. (2013)	Renault et al. (1995); Friedman et al. (2005); Garcia et al. (2011); Paul-Pont et al. (2013); Batista et al. (2015)
Bacteria				
Vibrio tubiashii[a]	*Crassostrea virginica* *Magallana gigas* *Ostrea edulis*	Vibriosis, Bacillary necrosis	Tubiash et al. (1965); Tubiash et al. (1970); Travers et al. (2014)	Jeffries (1982); Lodeiros et al. (1987); Elston et al. (2008); Hada et al. (1984) [a]
Vibrio splendidus related	*Magallana gigas*	Vibriosis	Le Roux et al. (2002); Gay et al. (2004)	LaCoste et al. (2001); Saulnier et al. (2010)
Vibrio aestuarianus	*Magallana gigas*	Vibriosis	Garnier et al. (2008)	Garnier et al. (2007); Mandas et al. (2020); Travers et al. (2015)
Roseovarius crassostreae	*Crassostrea virginica*	Roseovarius Oyster Disease (ROD) Juvenile Oyster Disease (JOD)	Boettcher et al. (1999, 2000); Boettcher et al. (2005)	Ford and Borrero (2001); Maloy et al. (2007); Boardman et al., 2008
Nocardia crassostreae	*Magallana gigas* *Ostrea edulis*	Oyster nocardiosis Fatal inflammatory bacteraemia (FIB)	Friedman and Hedrick (1991)	Elston et al. (1987); Friedman et al. (1998); Engelsma et al. (2008)
Protists				
Haplosporidium costale	*Crassostrea virginica* *Magallana gigas*	Seaside organism disease, High salinity disease	Wood and Andrews (1962); Perkins (1969); Arzul et al. (2022)	Andrews (1988); Andrews and Castagna (1978)
Haplosporidium nelsoni	*Crassostrea virginica*	MSX (Multinucleate Sphere Unknown X) disease, Delaware Bay disease Haplosporidiosis	Andrews (1962); Haskin et al. (1966)	Ford and Haskin (1982); Burreson et al. (2000); Burreson and Ford (2004)
Perkinsus marinus	*Crassostrea virginica* *Crassostrea corteziensis,* *Magallana ariakensis* *Saccostrea palmula*	“Dermo" disease Proliferative disease Perkinsosis	Mackin et al. (1950) Mackin (1962)	Andrews (1988) Carnegie et al. (2021); Cáceres-Martinez et al. (2008); Moss et al., (2006); Cáceres-Martinez et al. (2012)
Mikrocytos mackini	*Magallana gigas* *Ostrea edulis* *Magallana sikamea*	Mikrocytosis, Microcell disease of oyster, Denman Island disease	Farley et al. (1988)	Bower (1988); Quayle (1982); Bower et al. (1997); Elston et al. (2012)
Mikrocytos mimicus	*Magallana gigas*	Mikrocytosis	Hartikainen et al. (2014)	
Bonamia ostreae	*Ostrea edulis; Ostrea chilensis;* *Magallana ariakensis.*	Microcell disease, Bonamiasis, Bonamiosis, Haemocyte disease of flat oyster, Haemocytic parasitosis	Pichot et al. (1980)	Culloty and Mulcahy (2007); Elston et al. (1986); Engelsma et al. (2010)
Bonamia exitiosa	*Ostrea chilensis, Ostrea angasi,* *Ostrea edulis* *Ostrea equestris;* *Ostrea puelchana,* *Ostrea lurida,* *Magallana ariakensis,* *Crassostrea virginica*	Microcell disease, Bonamiasis, Bonamiosis, Haemocyte disease of oysters.	Hine et al. (1991b)	Buss et al. (2019); Hine et al. (1991a); Cranfield et al. (2005)
Marteilia refringens	*Ostrea edulis; Ostrea stentina*	Maladie des Abers, "Aber disease", Digestive gland disease, Marteiliosis.	Grizel et al. (1974)	Alderman (1979); Figueras and Montes (1988); Mérou et al. (2023)
Marteilioides chungmuensis	*Magallana gigas* *Magallana nippona* *Magallana ariakensis*	–	Comps et al. (1987)	Itoh et al. (2002); Park et al. (2003); Tun et al. (2006)
Marteilia sydneyi	*Saccostrea glomerata*	QX (Queensland unknown) disease.	Wolf (1972); Perkins and Wolf (1976)	Kleeman et al. (2002); Diggles (2013); Adlard and Nolan (2015)
Fungi				
Ostracoblabe implexa	*Magallana gigas* *Magallana angulata* *Ostrea edulis*, Saccostrea cucullata	Shell disease, Dutch shell disease	Bornet and Flahault (1889); Alderman (1976)	Hoeck (1902); Cole and Waugh (1956); Alderman (1985)
Parasitic copepod				
Mytilicola orientalis	*Magallana gigas* *Ostrea edulis, Ostrea lurida*	*Mytilicola* disease, Red worm disease	Mori (1935)	Deslou-Paoli (1981); Steele and Mulcahy (2001)
Mytilicola intestinalis	*Magallana gigas* *Ostrea edulis*	*Mytilicola* disease, Red worm disease	Baird et al. (1951)	Dare (1982); Aguirre-Macedo and Kennedy (1999a,b)
Other diseases				

(*continued on next page*)

Table 1 (*continued*)

Disease agent	Disease host (oyster species showing mortality and/or lesions when infected)	Associated disease(s)	Publications on the disease agent (first characterizations of agent)	Examples of publications on the disease itself (description of mortality and/or lesions)
-	*Crassostrea virginica* *Crassostrea tulipa* *Magallana gigas* *Magallana bilineata* *Saccostrea glomerata* *Ostrea edulis* *Ostrea lurida* *Ostrea chilensis*	Disseminated neoplasia (DN) Haematopoietic, Hemic or Haemocytic neoplasia (HCN)	Farley (1969)	Frierman and Andrews (1976); Ford et al. (1997); Barber (2004); Carballal et al. (2015); Da Silva et al. (2018)

[a] V. tubiashii taxonomy has changed over time and led to misclassification of some strains. For instance, Hada et al. (1984) V. Tubiashii reported by Hada et al. (1984) was recently reclassified as V. coralliilyticus.

Table 2

Risk reduction strategies for reducing the exposure and the vulnerability to oyster pathogen (Hazard 1) and disease outbreak (Hazard 2) occurrence (cf. Fig. 2).

	RISK to oyster population		RISK to coastal society	
	HAZARD: Oyster pathogen occurrence		HAZARD: Marine disease outbreak	
	EXPOSURE	VULNERABILITY	EXPOSURE	VULNERABILITY
Site evaluation	- Proximity to the hazard - Environmental dynamics (water depth, ocean current, …) - Transmission pathways - Disease history - Dispersal barriers (naturally occurring) - Affected hosts - Culture type (floating, bottom, …)	- Oyster species - Culture densities - Oyster health - Ecosystem health	- Proximity of coastal community to outbreak - How many farms exposed? - Production capacities - Coastal infrastructure	- (Strong) Dependency of coastal community - Oyster monocultures - Community well-being
Risk reduction options	- Early warning systems - Dispersal barriers (introduced) - Water treatment (UV) in hatcheries/ nurseries to decrease exposure to pathogens	- Vaccination-like approachesgr - Seed screening - Genetic selection programmes (to have more resistant oysters) - Transfer restriction - Regular health controls	- Timing of harvest decision - Information/awareness campaigns about exposure to risks - Land-based cultures with artificial sea water - Off-shore culture	- Aquaculture diversification - Livelihood diversification - Insurance solutions - Subsidies or tax exemptions - Alternative use (e.g. as animal feed) when oysters do not meet sanitary requirements for direct human consumption)

Different climate conditions will differently affect the likelihood of disease pathogens to occur (and/or to develop into a hazardous event) and hence the exposure of oyster populations and farm systems. Physical-environmental factors such as its distance to the coast, water depth and ocean current dynamics – all of which shape how well the surrounding waters are flushed – similarly shape the exposure of a culture site. In a well-circulated system (i.e. in one with a low water residence time), disease agents are easily "flushed away", i.e. exposure is decreased. And in a setting, where water residence times are high, pathogens have the chance to accumulate, hence the exposure to disease agents is potentially high as well. This relationship is likely not linear, though, because in a well-flushed system, oxygen (and potentially food) conditions presumably meet better optimal requirements of oysters, which can strengthen their capacity to withstand stressors. Exposure of oyster farms will also depend on the presence of "dispersal barriers" such as other filter feeders (removing pathogens from the environment through filtration before they can reach oyster farms) in the direct surroundings.

Exposure is also shaped by factors such as the frequency and intensity of pathogen occurrence in the particular setting, and on pathogen-related factors (e.g. virulence partly driven by genetic predispositions) and host-related factors (genetic, sex, age, oyster seed availability) (see Rodgers et al., 2019 for the example of OsV-1 and *Magallana gigas*). In the marine realm, connectivity of (eco-)systems and hence disease dispersal is multi-dimensional. And in the case of oysters, pathogens may either be transported via ocean currents (individually, or via oyster larvae as hosts) or humans (through the transfer of infected oyster seed) from one setting to the other. In fact, humans are the most important route of pathogen spread for oysters (Peeler et al., 2011). This makes the understanding of connectivity of oyster populations and related disease transmission pathways (as shaped by ocean dynamics and human activities) crucial (Schmittman et al., 2024) for defining exposure. Related, those oyster cultivation sites situated in regions where hosts (other oysters and other bivalves or other vectors) are abundant and/or where oyster farming is important will likely be more exposed than others (Arzul et al., 2021). Similarly, if pathogens have previously been recorded and/or disease outbreaks observed, a site will be more exposed.

The type of the oyster culture system also plays a role in framing exposure: A bottom culture is likely more exposed when compared to rafts deployed in the water column, which has to do with confounding factors such as oxygen availability (higher in water surfaces) and other variables generally affecting oyster health and by that their resistance towards stressors such as disease pathogens. Oyster grow-out densities (i.e. how many individuals are cultured per sqm or unit of culture) additionally affect likelihood of infection and further dispersal of pathogens.

5.1.3. Vulnerability of different culture systems to oyster disease pathogens

For our example at hand, we first have to consider the vulnerabilities of the farmed oyster population to pathogen occurrence. Here, cultured oysters and their direct environment are important: the type (species) and health of oysters farmed (e.g. individual and species-level genetic predispositions), the surrounding ecosystem (and its overall health status), composed of the physical space (water, sediments, hard structures, etc.) and abiotic surrounding (salinity, temperature, pH, pollutants, etc.) in which culture facilities (nets, meshbags, rafts, etc.) are placed, but also the biotic dimension (i.e. other species and wild oyster populations co-occurring with oyster cultures). All these factors shape the susceptibility of the oyster population to the impacts and consequences of

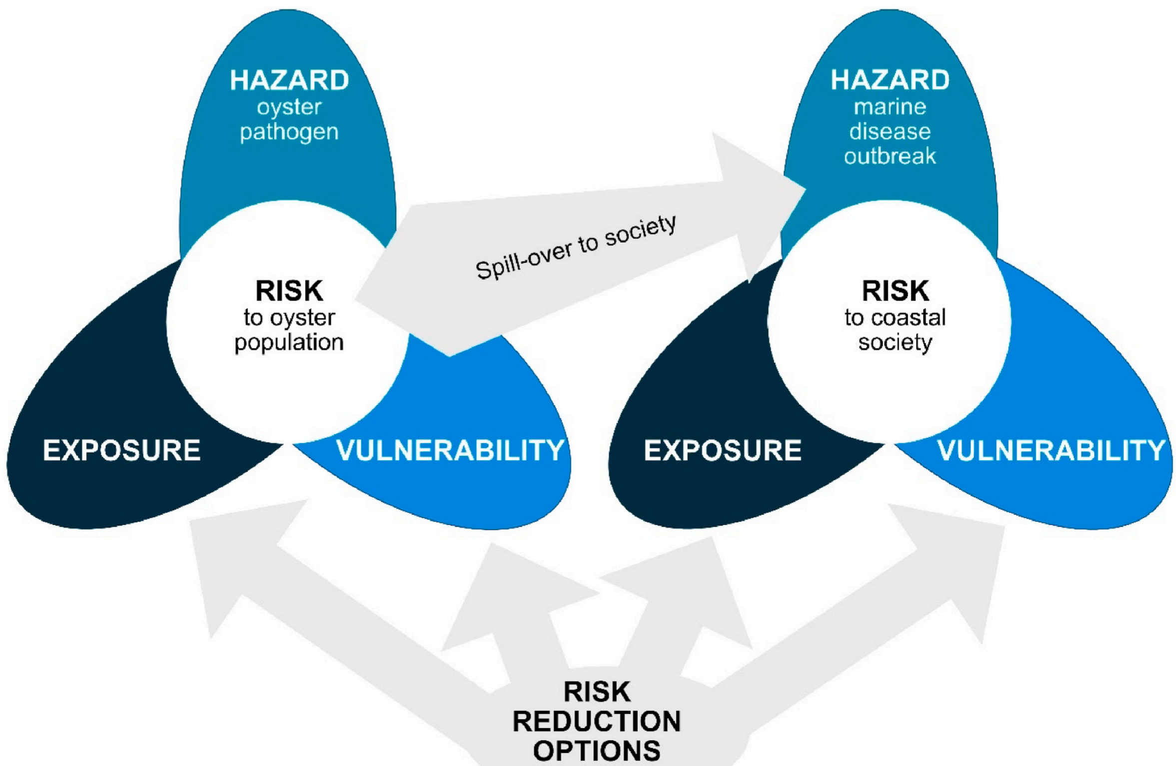

Fig. 2. Adopted risk UNDRR framework for the case study of farmed oysters (following Fig. 1) conceptualizing oyster pathogen occurrence as a hazard to the farmed oyster population, the risk being a composite result of oyster population's exposure and vulnerability to the hazard. The occurrence of a disease outbreak is then conceptualized as a cascading hazard to local (coastal) society, the risk of which is a composite result of the coastal society's exposure and vulnerability to the hazard.

pathogen loading. For example, oysters being farmed in an environment that already contains one or multiple stressors, e.g. high temperatures or low pH (as potentially shaped by climate change effects), are likely to be more susceptible to an additional stressor (pathogen occurrence) and less capable of coping with it when compared to oysters in environments with ideal growth and living conditions. This difference can potentially drive vulnerability and hence the likelihood, i.e. whether a disease outbreak will occur.

5.2. *Marine disease outbreak: a risk to coastal community?*

5.2.1. *Marine disease outbreaks as hazards to oyster coastal society*

Oyster culture takes place in the natural (coastal) environment, with both the oysters and their reefs and the environment itself creating crucial ecosystem services to society. We therefore argue that the risk of hazardous disease events cannot be estimated without discussing impacts on ecosystem service provisioning. In the following, these ecosystem services are structured into CICES's main sections: provisioning, regulation and maintenance, as well as cultural ecosystem services (*sensu* Haines-Young and Potschin-Young, 2018). Identifying actors directly and indirectly affected by oyster diseases is also crucial to suggest risk reduction options (*cf.* Section 5.3).

The impact of oyster diseases on **provisioning** (ecosystem) services is extensively documented. A focus is here often on the aquaculture industry rather than fisheries, likely because aquaculture production significantly exceeds wild harvest (FAO, 2022). Yearly global production of bivalves, including oysters, is estimated at over 15 million tonnes (Costello et al., 2021). In 2020, global exports of bivalve molluscs (including oysters) was estimated at USD 4.3 billion (FAO, 2022). For oysters in particular, for the Northeast Pacific coast (United States), the industry has been valued between USD 73 (McComas et al., 2015) and USD 300 million annually (Schuldt et al., 2016). From this, the economic consequences of marine disease occurrence become clear; marine diseases of bivalves "cost billions of dollars each year" (Lafferty et al., 2015).

Marine diseases impact the aquaculture industry primarily due to mortality of affected oysters. Mortality rates vary depending on the marine disease: from 30 to 70 % for Dermo disease (Guo and Ford, 2016; Carnegie et al., 2021), 70–90 % for MSX disease (Guo and Ford, 2016), 90 %–98 % for QX disease (Guo and Ford, 2016; Wilkie et al., 2012), 60–95 % for bonamiosis (Guo and Ford, 2016) and 90–95 % for Roseovarius (or Juvenile) Oyster Disease (Guo and Ford, 2016). Some scientific articles report mortality information about specific incidents. In 1986, due to bonamiosis 60 % of the oyster *O. chilensis* was lost in New Zealand, and six years later "only 9 % of the stock that was present in 1975 remained" (Guo and Ford, 2016). Ostreid herpesvirus 1 (OsHV-1) has been regularly detected and associated with mortality of larvae and spat (oysters younger than one year) *Magallana (Crassostrea) gigas* in France since the 90s (Nicolas et al., 1992; Renault et al., 1994; Garcia et al., 2011). Since 2008, a new genotype called OsHV-1 μvar has been characterized and associated with outbreaks mass mortalities (80–90 %) in oyster spat in France and then in other European countries (Segarra et al., 2010; Delisle et al., 2018, 2020).

Marine diseases may also have impacts on the aquaculture industry through increased production costs, e.g. related to post-harvest treatment (depuration or relaying) required in some areas with high risks of contamination (Qin et al., 2022). However, few analyses have estimated the financial impact of marine disease outbreaks for the aquaculture industry. On the example of Dermo disease, Lafferty et al. (2015) mentions "the total potential ex-vessel economic loss to Dermo equates to approximately US$6 million per year" in Delaware Bay (United States), but no information is provided on how this estimate was extrapolated.

Very few impacts are reported for the **fishing industry**. Some authors relate negative impacts to the fact that oysters support fisheries (Guo and Ford, 2016; Lafferty et al., 2015). At the same time, the interaction of oyster (cultures) with other species' populations relevant to fisheries (i.e. for which oyster (reefs) function as habitat and/or source of food) is important to consider. Schuldt et al. (2015) also suggest that diseases that pose a risk to human health may affect the public's perception of seafood safety, and thus decrease demand for raw seafood and impact commercial fisheries (Schuldt et al., 2016), with foreseeable (side)effects for (the perception of) other seafood industries as well.

Some studies hypothesize that marine diseases can affect oysters' capabilities to provide services related to **regulation and maintenance**. Oysters provide a variety of such services: filtration that improves water clarity, nutrient cycling and controlling blooms (Wilkie et al., 2012; Pernet et al., 2018; Burge et al., 2014; Guo and Ford, 2016; Lafferty et al., 2015), working as wave barriers and reducing bank erosion (Lafferty et al., 2015; Pernet et al., 2018), food resource for species such as crabs, whelks and fish (Wilkie et al., 2012; Burge et al., 2014) and providing shelter and habitats for other invertebrate and fish species (Pogoda et al., 2019; Wilkie et al., 2012; Pernet et al., 2018; Burge et al., 2014; Guo and Ford, 2016), i.e. function as ecosystem engineers (*sensu* Jones et al., 1994, 1997). The link between oyster diseases and their impact on regulating services seems to be due to increased mortality: as oyster individuals die and thus overall populations decline, the regulating services they provide are reduced. There are no direct reports of a specific disease affecting regulating services differently.

None of the analysed papers mentioned impacts of disease outbreaks on **cultural services** specifically. This is striking as the cultural value of oysters is high: Regional recreational activities and tourism for example profit from nutrient filtering and successive improvements in water quality (Lipton, 2004; Lemasson et al., 2017). Oysters as well as oyster production are deeply embedded in local heritage, traditions and history, even dating back to Roman times (Mouchi et al., 2018; Lõugas et al., 2022) and to colonial times in the USA (Freitag et al., 2017). A variety of festivals around the globe cherishing oysters reflect the importance of cultural value: the Foire aux Huîtres in France, the Galway Oyster Festival in Ireland, the Narooma Oyster Festival in Australia, the New Orleans Oyster Festival, the Whitstable Oyster Festival in England or the Bluff Oyster and Food Festival in New Zealand. Marine diseases leading in the worst case to the disappearance of oyster (production) would thus disrupt the cultural service provisioning, potential reducing pride and traditions. And particularly where those traditions nourish the tourism sector this would result in negative socio-economic impacts. The aforementioned aspects mainly relate to the link between oyster diseases and oyster population die-offs, and cascading socio-economic losses for local society. But nearly all ecosystem services can have impacts on (human) health, e.g. providing food (provisioning), maintaining biodiversity and infectious disease control (regulation and maintenance) and cultural services (Lindgren and Elmqvist, 2017).

Yet, waterborne pathogens with a potential direct impact on human health can accumulate in oysters without directly affecting oyster mortality and oyster population sizes. This means that risk perpetuation pathways and respective reduction options are different. Then, oysters bearing pathogens would be the hazard to society. Impacts on human health are heavily reported for some human pathogenic Vibrios in oysters, and NovoVirus outbreaks to a lesser degree. Human illnesses due to vibrio arise when infected oysters are consumed raw (McComas et al., 2015), and while these pathogenic vibrio species (e.g. *Vibrio parahaemolyticus, Vibrio cholerae*) do not affect oysters directly, they are the leading cause of "seafood-related illnesses" (Bienlien et al., 2022), such as human gastrointestinal illness, septicaemia or cellulitis (Groner et al., 2016). Pathogenic vibrio may also lead to death in humans "with a 50 % fatality rate due to rapid development of systemic infections and acute septicaemia" (Schuldt et al., 2016; Bienlien et al., 2022). Controlling outbreaks due to pathogenic vibrio is an urgent food safety issue. Management options after an outbreak has occurred include "targeted surveillance methods" (Cantrell et al., 2020), and once an outbreak has been identified, managers can close the affected area, issue advisories and "initiate a recall of oyster and other shellfish products" (Groner et al., 2016). Here, we focus on the indirect effects.

5.2.2. Exposure of local society to the hazard 'oyster disease outbreak'

The exposure of local communities to disease outbreaks is shaped by contextual characteristics such as aquaculture intensity (how many oyster farms are present) and other human activities taking place in the same coastal space. If the disease outbreak manifests, exposure to marine disease occurrence may be evaluated by characterising the economic agents affected by a change in oyster populations, for example the aquaculture owner (including the size and intensity of the farming activity), employees in oyster farming and in the post-harvest sector (processing, transport, merchants, etc), the end consumers of oysters, but also any individual that values the oyster species for any reason, e.g. if one has existence or bequest (i.e. *non-use*) values towards oyster populations (Krutilla, 1967). Physical distance of economic agents to the affected area also explains exposure to the marine disease outbreak. One can conclude that every beneficiary of ecosystem services provided by oyster cultures is exposed to a disease outbreak.

5.2.3. Vulnerability of local society to the hazard 'oyster disease outbreak'

Cultural, socio-economic and political settings of the local society in which an oyster culture takes place influence the degree to which a hazardous event (i.e. a disease outbreak in the oyster culture) will have an effect on the coastal community (and beyond). And social susceptibility will likely be shaped by the livelihood portfolio of local society, and thus be a product of the individual vulnerabilities of existing economic sectors therein. Vulnerability will therefore depend on the degree to which the local society depends on the ecosystem services provided by oyster farming. Thus, an understanding of these factors is vital for disease risk reduction. For example, a larger producer with financial stability, a diverse portfolio of seafood products, and/or insurance, is less vulnerable to the occurrence of a hazardous event (i.e. a disease outbreak affecting a seasonal harvest) than small-scale producers with few or no savings. Jamwal and Phulia (2021) elaborate on this for the case of human pandemics. Whether or not insurance (against losses from disease outbreaks or other harvest failures) is available (and accessible) and/or state policies support producers in distress will additionally play a role in the vulnerability debate. And similarly, if a local society is (economically, job-wise) strongly dependent on oyster culture, i.e. if few alternative livelihood options exist for those involved in the sector, a disease outbreak and resulting mass mortalities of oysters are likely to generate a larger impact than for a community that has a diverse set of options to generate income to draw from amidst such a crisis. Thus, vulnerability of the local community to the hazard disease outbreak depends very much on its ability to cope and adapt to such an event, which in turn is influenced by political settings.

5.3. Resulting risk reduction options

Having discussed the ways how hazard, exposure and vulnerability shape the risk to society associated with marine diseases in oyster cultures, one can derive a wide set of risk reduction options (Table 2). The structured summary of these options represents the clear contribution of the present work and should be seen as potential guiding elements to risk reduction management beyond purely theoretical progressions. Exposure of the ecological dimension of a social-ecological system may be reduced by careful site selection, e.g. considering environmental conditions such as the flushing of the system and the pre-existence of pathogens and/or their hosts, and disease outbreaks in the past. Related, the existence (or introduction) of other filter feeders, forming a dispersal barrier, or implementing artificial flushing as to reduce pathogen exposure can be a possibility. Selecting a culture facility that is best suited to minimize exposure (bottom vs. floating culture systems) is of importance, adjusting culture conditions (e.g. oyster densities) and harvest decisions (e.g. collect oysters before specific times of the year, for which disease outbreaks have been reported) will likely reduce exposure. The most promising point may be to tackle the most important dispersal pathways, e.g. through implementing oyster seed screening or check-ups of adult oysters to be transferred somewhere, all with the goal of reducing the amount of pathogens and infected individuals entering or leaving a farm. Similarly, Arzul et al. (2021) suggested implementing transfer restrictions, calendars for disease-sensible stock management, selection programmes and water treatments for hatcheries/nurseries.

Vulnerability may be reduced by strengthening the capacity of each actor to confront the occurrence of a hazardous event (i.e. a disease outbreak) and its consequences. For the ecological systems, this can mean selecting species (or individuals) resistant to disease present in the particular environment or implementing vaccination strategies for those individuals frequently introduced to farms. For most humans, actions to reduce vulnerability likely relate to financial means to deal with losses from a bad harvest, and insurance covering such losses plays an important role here. But it is also important to discuss the option to decrease vulnerability of farmers by reducing the single-species dependency of their work via creating alternative incomes from a diverse set of livelihood options. Be it through other ocean-based income sources, e.g. the cultivation of other species such as algae together with the bivalves, or land-based activities, for example tourism and transport.

It goes without saying that the hazard in the ecological realm cannot be reduced, or avoided completely. (Coastal) Management and community initiatives can only aim to reduce exposure and vulnerability of oyster cultures to pathogen occurrence. Yet, by addressing the exposure and vulnerability dimensions in the ecological realm, it is possible to alter the hazard for the social realm, reducing the likelihood of a disease outbreak and socio-economic repercussions for coastal communities. Adding this social-ecological view to the hazard scenery clearly helps in deriving actionable strategies by improve preparedness of the entire SES to future disease outbreaks.

6. Discussion: the way forward

To our knowledge, the risk framework commonly used in the Disaster Risk Reduction as well as Climate Change Adaptation communities has not been applied systemically to marine diseases yet. And reviewing the targets of international organisations being concerned with diseases (*cf.* Appendix 2 for an overview), one may conclude that the focus typically rests on animal, plant and/or human health and their risk to experience negative impacts from disease occurrence. The social domain of concerned social-ecological systems is discussed, if at all, via human health or economic risks emerging from diseases affecting commercially used species. Risk reduction options are then tailored towards reducing the likelihood of disease outbreak occurrence via effective monitoring or actions addressing the individual species level. In the present work, in our adapted risk framework, we go beyond human health for the discussion of societal impacts: Our system approach allows to illuminate the extended involvement via the lens of ecosystem services. In addition, the consideration of the risks-components hazard, exposure and vulnerability both for the ecological and societal part, with the actual disease outbreak interpreted as hazard, allows the identification of additional options for targeted prevention measures. Herein, we argue that integrating marine diseases into current hazard landscapes can crucially support knowledge integration across different disciplines and provide a tool to deduce management options in the different domains. This structuring equally promotes clear science communication and can be understood as an investment in social resilience beyond theoretical explorations. The outputs of risk assessment are inputs into decision-making on managing risks (UNISDR - United Nations Office for Disaster Risk Reduction, 2018). Transparent risk communication is essential to assure consensus among stakeholders with different feasibilities and needs (Bartley et al., 2006) and can benefit from standardized, transparent approaches as suggested herein. After the identification of actors (social-ecological components) affected by hazardous events and drafting risk reduction options, it is crucial to discuss these actions in light of (shared and individual) responsibilities. A wide range of different actors potentially responsible for implementation emerge, as mitigation can take place in the exposure or vulnerability domain of both the ecological and the social system. As an example, the establishment of an early warning system using environmental indicators (as to reduce exposure in the ecological system) needs support from ecological scientists, whereas vaccinations-like approaches (as to reduce vulnerability in the ecological system) need support from veterinarians and biologists and finding and/or establishing suitable insurance options (again reducing vulnerability, but in the social system) would require the help of businesses and economists, or could be done by the aquaculture company itself. Accordingly, the state involvement will also differ depending on the mitigation strategy and different regulatory bodies and governmental agencies such action touches. This diversity in responsibilities represents challenges as well as opportunities for both the adapted framework presented herein, and for articulating actionable management strategies. Challenges emerge, because identifying risk reduction strategies requires an inter- and transdisciplinary view on manageable strategies. And opportunities arise because achieving such a joined perspective is likely to also facilitate implementation of actions. We are convinced that our framework provides a structured environment that helps to consider a common threat – a marine disease outbreak – without being constrained by disciplinary conceptions, to facilitate the co-development of robust coastal management initiatives by different scientists and (coastal) stakeholders.

Yet, risk reduction options will not be developed amidst a white wall, but are bound to (non-)existing regulatory frameworks that may create an inhibitory or promotive environment for the design of such measures and adaptive processes in general. Depending on the social and economic capabilities and (political) willingness of individual and state actors, mitigation options may in practice be implemented at an accelerating rate and with wide-ranging effects, or be reduced to a rather cosmetic scope. When aiming to put outlined risk reduction options into practice, it has thus to be considered that there are already existing regulations, which might have to be drafted, reformed and/or expanded, but which cannot simply be ignored as they present the broader multi-level regulatory framework in real-world politics. As such, policy makers and management practitioners alike play crucial roles in promoting – or hindering – drafting and implementing meaningful risk reduction actions as to increase preparedness to pathogen occurrence and marine disease outbreaks (Karunasagar, 2008). Overall, it is important to highlight that existing (though fragmented) regulations are exclusively tailored towards pathogens that are already known, have been described and its effects studied. Little do we know, however, on future (oyster) disease outbreaks emerging from yet undiscovered pathogens, their effects on local oyster aquaculture and societies – and thus respectively required governance approaches to stem those effects. Considering the somewhat surprising magnitude of effects from recent pandemics, there is an urgent need for more adaptive governance approaches, including a close cooperation of science and responsible (political) authorities, but also aquaculture business, to act accordingly. The risk framework for oyster pathogens presented in this study is crucial for assessing risks emerging from future hazards and for guiding future management action and legislation frameworks. We believe that by articulating risk reduction options for one particular example of disease, one can improve coastal management strategies and thus enhance SES preparedness to diseases outbreaks.

Oceans and humans are irrevocably interconnected, and marine diseases can both directly and indirectly affect human health, livelihoods and well-being. This work uses oyster aquaculture as a case study to demonstrate that adopting the UNDRR risk framework to marine diseases is helpful in many ways. First, it allows to identify consequences of oyster pathogen diseases as an environmental hazard. Secondly, it facilitates to determine affected actors of a disease outbreak (as a cascading hazard affects the socio-economic domain of the social-ecological system). While the UNDRR risk framework focuses mainly on natural and human disasters with societal impacts, other frameworks such as the one of the World Organisation for Animal health (WOAH) target diseases; the WOAH provides overviews of animal disease situations and designs (animal) health standards for international trade without considering spill-over effects of disease outbreaks or looking into mitigation and/or adaptation strategies. Our work is thus a complement to both of these efforts by adding the contemplation of disease situations to the UNDRR perspective. We present risk reduction options to decrease exposure and vulnerability ranging from dispersal barriers or seed screening to diversification or insurance solutions. And by decreasing risk in the ecological realm, the risk for the social realm is reduced. Our interdisciplinary approach, focusing first on oyster pathogen occurrence and then on the outbreak and its implications for society (spill-over), can be transferred to any other marine host, providing structured, transparent and transferable guidance to policy-makers and decision-takers alike. Legal frameworks focus as yet on the known, leaving aside the obscure threats emerging from future marine diseases. Overall, this paper finds rich literature documenting risk to oyster populations, but scarce analysis estimating the socio-economic impacts of disease outbreaks. Despite its economic significance, to date no analysis has estimated the financial impact of marine disease outbreaks for the aquaculture industry, but also for coastal communities. More research illustrating the significance of these impacts is needed, especially for the case of oyster populations. We argue that better monitoring and response networks as well as enacting policies addressing marine diseases is crucial to maintain and promote ecosystem integrity (and by that ocean health) and sustain ecosystem services important to humans. All of this is particularly important considering the low impact nature of bivalve (oyster) culture and the role of marine diseases as a potential indicator of ecosystem equilibrium, an early warning for acting upon ecosystem health in general.

CRediT authorship contribution statement

Lotta Clara Kluger: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Svenja Karstens:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Ana Faria Lopes:** Writing – review & editing, Writing – original draft, Methodology. **Annegret Kuhn:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Isabelle Arzul:** Writing – review & editing, Conceptualization. **Marie-Catherine Riekhof:** Writing – review & editing, Methodology, Conceptualization.

Declaration of generative AI and ai-aisssted technologies

No generative AI or AI-assisted technology was used for the preparation of this manuscript and the elaboration of its content.

Declaration of competing interest

The authors declare no competing interests.

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APPENDIX 1

Overview of methodological approach

We started our analysis with two types of literature reviews: first to clarify the concept of marine diseases and then to examine debates surrounding our case study. Next, we adapted the existing Sendai risk framework to the case of social-economic systems by a) including the concept of ecosystem services based on the CICES framework (CICES = Common International Classification of Ecosystem Services; Haines-Young and Potschin-Young, 2018) and b) advocating for an anticipatory risk management strategy: elaborating risk reduction options for within the risks determinants exposure and vulnerability as to decrease the likelihood of occurrence of a hazardous event (instead of retroactive responses as do Simpson et al., 2021). We then apply this adapted framework to farmed oysters (*Crassostrea/Magallana* spp., *Ostrea* spp. *Saccostrea* spp.) as a case study for marine diseases.

The first literature review was structured and purposive, and conducted on August 16, 2022 (for records from 1945 to 2022) using the core collection of ISI Web of Knowledge (www.webofknowledge.com). The search string consisted of keywords relevant to marine diseases (i.e. "marine disease*" OR "marine infectious disease*") and was defined through several rounds of discussion with all authors. Only peer-reviewed articles (including reviews) published in English were considered. This resulted in 135 studies, for which full records and pdfs of articles were downloaded. All articles were screened.

Then, we aimed to identify all work – within this list of 135 retrieved papers – that discussed "oysters". For this, we developed a routine using the R software (R Core Team, 2022) and the packages *pdf_tools* (Ooms, 2019) and *corpus* (Perry, 2017) to look for any paper mentioning the term "oyster". Out of these, the R routine identified all papers that mentioned (1) societal impacts of marine diseases (i.e. by screening for terms like "societ", "health" and "human"), (2) economic impacts of marine diseases (i.e. by screening for terms like "econom", "financ", or "profit"), and (3) governance of marine diseases (i.e. by screening for terms like "govern", "management", "politic", "regulat", "health policy", and "legislation"). From the 135 papers identified in the first step, 60 mentioned the term oysters and 21 papers were then identified as qualified sources of information for the three categories described before. This systematic literature review and its analysis were complemented by a purposive literature review based on the list of marine diseases presented and discussed in Lafferty (2017, who expanded and complemented this from Lafferty et al., 2015). To complement the search, we followed a snowball-approach, i.e. identifying more literature from those work found before.

All these steps were used to fill adapt and the categories of the UNDRR Risk framework (as presented in the manuscripts section 4 and 5). But: Vulnerability and impact assessments are closely linked (e.g. Toro et al., 2012; Aslam et al., 2017; Apreda et al., 2019). And since oyster (culture) takes place in the natural (i.e. coastal) environment, with both the oysters and their reefs and the environment itself creating crucial ecosystem services to society, the risk of hazardous disease events cannot be considered without discussing impacts for ecosystem service provisioning. Identifying actors directly and indirectly affected by oyster diseases is also crucial to suggest risk reduction options (section 3.3). To structure the impact analysis, we follow the CICES ecosystem service classification system (Haines-Young and Potschin-Young, 2018). The impacts of marine diseases affecting oysters are categorized into CICES's three main sections: provisioning, regulation and maintenance, and cultural ecosystem services.

APPENDIX 2

Overview of international conventions and organisations concerned with diseases

Table A2.1
Overview of international organisations and conventions addressing diseases, illuminating respective target organisms and focus taken on diseases.

Name of organisation	Target organisms when addressing diseases	Aspects of disease addressed	References
United Nations Office for Disaster Risk Reduction (UNDRR)	Humans, Animals, Environment	– "Prevention of new disaster risks" – "Reduction of existing risk" – "Promoting the strengthening of resilience"	URL 1
World Organization for Animal Health (WOAH)	Animals (terrestrial and aquatic), humans and environment indirectly	– "Monitoring the emergence and development of animal diseases" – "Improving animal health and welfare globally" – "Controlling animal diseases" – "Eradication of animal diseases" – "Prevention of zoonotic diseases" – "Better access to animal health care" – Strengthening international solidarity in the control of animal health risks	URL 2, URL 3
CODEX Alimentarius Comission (CAC)	Animals	– "Maintaining fish free of disease to the extent possible" – "Fish should be routinely monitored for disease"	URL 4
World Health Organization (WHO)	Humans directly, animals indirectly via zoonotic diseases	– "Shifting disease burden" – "Ending diseases" – "Fighting against the disease" – "Aim of wiping out the disease"	URL 5
International Plant Protection convention for plant health	Plants, ecosystems	– "Raising awareness on the disease and its control"	URL 6
Sanitary and Phytosanitary Agreement (SPS, of the World Trade Organization, WTO)	Plants, animals, humans	– Protecting animal or plant life or health from disease-carrying organisms or disease-causing organisms	URL 7
Food and Agriculture Organization of the United Nations (FAO)	Plants, animals, humans, ecosystems	- "to prepare, prevent and control pests and diseases" - "surveillance and risk assessment" of animal and zoonotic diseases	URL 8 URL 9
International Council for the Exploration of the Sea (ICES)	Animals, (marine) ecosystems	- "reviews and reports on the health challenges affecting wild and cultured marine species"	URL 10
Intergovernmental Oceanographic Commission (IOC)	(Marine) Ecosystems	– "Integrating epidemiology and climate information helps understand and anticipate those diseases sensitive to climate."	URL 11

[URL 1] https://www.undrr.org/our-work/our-impact.
[URL 2] https://www.woah.org/en/world-leaders-and-experts-call-for-action-to-protect-the-environment-from-antimicrobial-pollution/.
[URL 3] https://www.woah.org/app/uploads/2021/05/en-oie-aahs.pdf, page 19.
[URL 4] https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXC%2B52-2003%252FCXC_052e.pdf.
[URL 5] https://iris.who.int/bitstream/handle/10665/376869/9789240094703-eng.pdf?sequence=1.
[URL 6] https://openknowledge.fao.org/server/api/core/bitstreams/66440c1e-1976-46a2-82b6-1468eba6c4aa/content, p. 58.
[URL 7] https://www.wto.org/english/docs_e/legal_e/sps_e.htm#art6, Annex A, 1a.
[URL 7] https://www.fao.org/one-health/areas-of-work/biosecurity/en.
[URL 9] https://www.fao.org/animal-health/areas-of-work/surveillance-and-risk-assessment-and-response/en.
[URL 10] https://ices-library.figshare.com/articles/report/Working_Group_on_Pathology_and_Diseases_of_Marine_Organisms_WGPDMO_outputs_from_2024_meeting_/28343924?file=52123748.
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Data availability

Data will be made available on request.

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