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Preventing and mitigating farmed bivalve disease: a Northern Ireland case study

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Abstract
Shellfish production forms a large proportion of marine aquaculture production in Northern Ireland (NI). Diseases represent a serious threat to the maintenance and growth of shellfish cultivation with severe consequences to production output and profitability. In Northern Ireland, production generally benefits from a good health status with the absence of notifiable diseases, except for localised cases of *Bonamia ostreae*, *Marteilia refringens* and ostreid herpes virus. In this paper, we qualitatively explore that the prevalence, risk, impact, mitigation and experience shellfish farmers in this region have in relation to disease. Sixteen semi-structured interviews were conducted with stakeholders within the sector. The interviews were transcribed verbatim, and Nvivo 12 was used to facilitate an inductive thematic analysis. Our results highlighted that the industry has varying attitudes and experiences with disease. At present-day temperatures, disease is not an issue and this provides vast market opportunities for the region. However, disease outbreaks have led to detrimental consequences to financial income, production output and reputation in the past, whilst control and mitigation remain reactive. It is imperative proactive disease prevention and control that are employed and enforced to sustain NI's reputation as a healthy shellfish region, particularly under increasing global temperatures and intensified production systems. A cultural shift to disease appreciation, risk analysis and surveillance through research, education, training and collaboration is essential. This study highlights the importance of providing a bottom-up communication platform with the stakeholders directly involved in shellfish culture and management, the value of cross sector engagement and the need to improve knowledge transfer between science the sector.

Keywords Aquaculture · Bivalve mollusc · Disease · Farmer's perspective · Qualitative

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Introduction

Aquatic food makes an important contribution to human health and development as an essential source of high-quality proteins, vitamins and micronutrients (Lauria et al. 2018; Jennings et al. 2016). These foods are sourced from the capture fisheries (wild) and aquaculture (farming) sectors (DAERA 2018). Security of aquatic food sources is of increasing concern as wild stocks plateau and begin to reach their maximum sustainable potential (Jayasinghe et al. 2016; Oidtmann et al. 2011; Cressey 2009). These concerns are exacerbated by the fact the human population is rapidly growing towards an estimated 9.8 billion people by 2050 (United Nations 2017). As a result, aquaculture production has become increasingly important in meeting demands for aquatic food and has become the fastest growing food producing sector in the world (FAO 2018; Oidtmann et al. 2011). It has been estimated that aquaculture production will need to more than double to 140 million tonnes by 2050 if we are to continue to meet the future demands for fish and shellfish as a food product (Waite et al. 2014).

The European Union (EU) is one region which provides a large market for aquaculture products and is the world's largest importer of seafood. However, despite this demand and the increasing global rate of aquaculture production, growth within EU countries has stagnated over the last 20 years. The spread of diseases has been one of the factors attributed to this stagnated production, and in some cases, responsible for social and economic disruptions at a national level (Oidtmann et al. 2011). Within the EU, there are 27 member states; each country shows different growth patterns due to varying regulatory settings on licences, use of water, veterinary medicines, emissions, species, production methods and environmental conditions (EC 2009). The largest proportion of production is shellfish, contributing 60% of the total tonnage of EU aquaculture production (Murray et al. 2012). The diseases associated with bivalve production include Bonamiasis caused by *Bonamia ostreae* and more recently the emergence of Ostreid Herpes virus type I (OsHV-1) that has dramatically affected the culture of the Pacific oyster *Magallana gigas* (Segarra et al. 2010). It is imperative to explore the situation in each member state individually if the EU is to provide area-specific solutions and optimise the overall productivity and profitability of the sector and contribute to global food security for present and future generations.

Within the EU, it is widely acknowledged that the Island of Ireland (IoI) has all the features for a thriving aquaculture industry and can become a prosperous producer and exporter of aquatic food. In particular, Northern Ireland (NI) has a unique disease free status for a number of notifiable diseases and suitable temperature regime, which makes it attractive for aquaculture production. This potential was recognised by the NI executive who set out ambitious targets to grow the fish and aquaculture sectors in their Going for Growth Strategy (Table 1). This was also followed up by the SEA FLAG Development Strategy 2018-2020 that was developed to help sustain Northern Ireland fishing communities. These targets for 2020 were ambitious and due to BREXIT and more recently COVID restrictions may not have been realised. However, there is still the recognition that the fish and aquaculture industry in NI is an area for growth.

Similar to the EU, shellfish production for human consumption forms the largest component of aquaculture in this region with 57 farms licensed in 2018 for the cultivation of mussels (*Mytilus edulis*) and Pacific Oysters (*Magallana gigas*). In NI, the shellfish farms are located across the region's coastal loughs, namely Belfast, Carlingford, Larne, Strangford, Dundrum Bay, Killough Bay and Lough Foyle (Fig. 1). Currently, the main method for mussel

Table 1 NI executive fish and aquaculture targets for 2020 (AFSB 2013)

Fish and aquaculture 2020 targets		
Grow turnover	By 34%	To £90m
Grow value-added	By 45%	To £22m
Grow external sales	By 36%	To £75m
Grow employment	By 9%	To 600 full time equivalents

production relies on wild caught seed dredged from wild mussel beds and relayed on licensed aquaculture sites for on-growing to harvestable size. The main cultivation method for Pacific oysters is bag and trestle cultivation. This method involves putting oysters in plastic mesh bags (pouches) and attaching them to metal framed structures called trestles in the inter-tidal zone. Pacific oysters (*M. gigas*) are not native to NI waters, and thus, the sector relies heavily on imported spat, predominantly from hatcheries in France and, to a much smaller extent the UK. The main exporter for Pacific oysters is France, but there are growing markets in Asia and the Middle-East (DAERA 2018). Although the region is described as a prosperous producer of shellfish, the productivity of the sector has decreased substantially from 11,081 tonnes in 2010 to 5,831 tonnes in 2016 (Table 2). It is important to note that these figures do not account for production in Lough Foyle (circled in red in Fig. 1) where there are an estimated 30,000 unlicensed oyster trestles (BBC News 2016). This Lough shares a border with the Republic of Ireland, and both regions are in a political dispute over ownership. As a result, neither authority has the power to regulate or control the spread of oyster farmers.

Diseases are one of the biggest threats to the maintenance and growth of shellfish cultivation (Jennings et al. 2016; Marquis et al. 2015; Oidtmann et al. 2011; Murray et al.

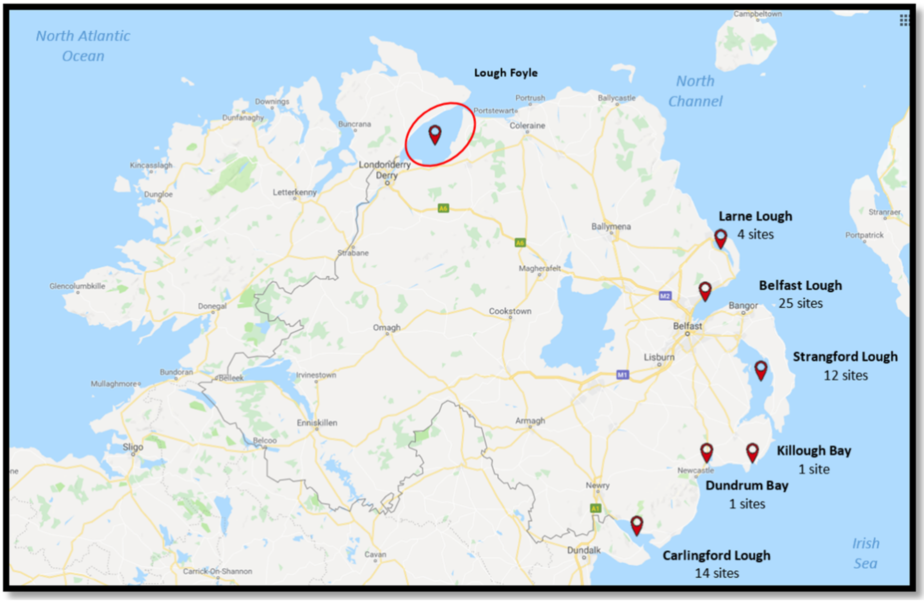

Fig. 1 Licensed shellfish production sites in NI. Shellfish production in NI is located across six coastal sites. In addition, there is unregulated production in Lough Foyle (circled in red) as this lough shares its border with the Republic of Ireland and there is a political dispute of ownership

Table 2 Production and value of the aquaculture sector in Northern Ireland

	2010		2017	
	Tonnes	£('000)	Tonnes	£('000)
Finfish	1155	3100	1248	6814
Shellfish	11,081	7700	5831	9074
Both	12,236	10,800	7079	15,888

2012). At present, NI is declared free of a number of shellfish diseases. However, notifiable diseases exist for: *Bonamia ostreae* in Lough Foyle and Strangford Lough, Ostreid herpes virus (OsHV-1 μVar) (only Lough Larne is free) and as of 2017, *Marteillia refringens* in Belfast Lough and Dundrum bay (DAERA 2018). These diseases have had devastating consequences to farmers within the region in terms of productivity, financial return and reputation (Peeler et al. 2012). It is imperative to understand the risk from disease and provide innovative solutions and long term management to the sector. This is particularly important for agri-food sector in NI as they set out to increase production in line with the targets set by the NI executive. Such growth is commonly associated with an introduction of new species and systems, and an increase in international trade. These factors exacerbate the spread and emergence of current and emerging diseases (Oidtmann et al. 2011). This study aims to identify and review the vulnerabilities of molluscs farmed in Northern Ireland to these pathogens based on the experiences and perspective of the stakeholders, explored using qualitative research methods. The study has a particular focus around key topic areas including key pathways for disease introduction, environmental conditions when disease strikes and the likelihood and consequence of disease outbreaks. These results can be used to assess the scale of risk to investment in mollusc production, key risk factors for disease, and consider if these could potentially be controlled and mitigated against to reduce the risk to production posed by disease.

Methodology

Participant recruitment

Stakeholders in the shellfish supply chain within Northern Ireland were recruited to take part in a semi-structured interview via stratified random sampling. Recruitment methods involved sending invitations via post and email to the farmers licensed to conduct shellfish cultivation and the agencies or government departments directly involved in sampling, licensing, enforcing or supporting the sector within Northern Ireland. The participants were divided up into sub-groups (strata) based on (1) their activity in the supply chain, (2) species cultivated and (3) location. Subsequently, the participants were randomly selected from each strata until response saturation was achieved. In total 16 stakeholders made up of shellfish farmers, government, food inspectors and independent agencies were interviewed. All participants provided informed verbal consent, and the study was approved by the School of Biological Sciences Ethical Committee at Queen's University Belfast (Table 3).

Table 3 Characteristics of interview participants

Characteristics		No. stakeholders	Interviews	
			N	%
Activity	Farmers	24	12	50
	Processors	1	1[1]	100
	Government	1	1	100
	Non-governmental	2	1	50
	Food inspector	3	2	67
Species	Oyster farmers	13	9	69
	Mussel farmers	8	3	38
Aquaculture production business (APB) location	Antrim	3	3	100
	Derry	Unknown[2]	1	Na
	Down	21	8	38

[1] One stakeholder in the shellfish industry is a farmer and a processor; thus, the number of stakeholders equals 17, but the number of interviews conducted equalled 16

[2] Unregulated shellfish production in Lough Foyle due to the jurisdictional issue

Interview questioning guide

Based upon a review of previous literature and the opinion from a number of experts involved in the aquaculture supply chain, the interview instrument was constructed. The interview guide was piloted for clarity, comprehension, reliability and timing with three individuals and refined prior to implementation. The questions were designed to elicit participant's perceptions regarding their experiences with shellfish production including their activity in the supply chain, the prevalence and threat of disease to their production; and mitigation measures (Table 4).

Table 4 Questioning route of semi-structured interviews

Section	Questions
Introduction	1.Brief overview of the project and interview
Supply chain	2.Can you tell me a bit about your production system/activity in the supply chain?
	3.How did you begin working within the aquaculture sector, motivation and start-up?
Disease	4.Can you tell me a bit about disease and if it affects your production system?
	° Characteristics, consequences and contributing factors
	° Changes in disease frequency or type
	° Impact and degree of mortality
	° Consumer perception
Mitigation	5.What kind of preventative measures do you implement for disease?
	a.Factors including in biosecurity plan
	b.Monitoring, biosecurity, analytical tests and methodologies
	c.Voluntary or regulatory—has there been any training or guidance provided
	d.Review of disease risk and how often
	e.The cost of mitigation—is it necessary or economically viable to implementing enhanced measures
	f.Certification schemes
	g.Water classification
Close	6.Summary of interview discussion. Is there anything else you would like to add?
	7.Thank you for taking time to participate in the survey

Data collection

Interviews were conducted face-to-face (n = 15) and by telephone (n = 1) between July 2017 and July 2018 by an interviewer (MF; a Food Quality, Safety and Nutrition Scientist) trained in qualitative data collection and interview techniques. Interviewees were given a brief overview of the project and reassured there was no right or wrong answers, they could opt out at any time and their data would remain confidential and anonymous. Verbal approval for audio recording was sought before the interviewer proceeded to ask a series of guided open-ended questions (Table 4). The interview concluded when all topics had been covered and no new information emerged. Interviews were audio recorded with a mean duration of 45 min.

Data analysis

Audio recordings were transcribed verbatim, checked for precision and coded thematically using the qualitative program Nvivo 12 (QSR International Pty Ltd, Victoria, Australia). The emphasis of the study was on the stakeholder's perceptions, and the analysis evaluated disease in the aquaculture sector from the subject's point of view. The transcripts were coded and independently checked for coding consistency before consensus on the validity and reliability of the application of codes to the data that were reached. Data saturation had occurred as no new relevant codes emerged from the interviews. Subsequently, codes were grouped into themes which represented a common principle. and illustrative quotes, which exemplified the theme, were selected. Finally, the themes and quotes were inspected for overlap to ensure there was a clear distinction within and between each of the themes and to confirm the data were presented objectively.

Results

The stakeholders involved in shellfish cultivation mentioned three different shellfish pathogens causing diseases: Ostreid herpes virus, *Bonamia ostreae* and *Marteilia refringens*, related to cultivation in Northern Ireland. There were a number of different attitudes related to the prevalence of disease:

(1) Not an issue.
"Disease isn't an issue" (*Mussel farmer*).
(2) The risk of disease is uncertain.
"It is fair at the minute it was higher at a time and you don't know what is around the corner either." (*Oyster farmer*)
(3) Not sure if disease is a contributing factor to mortality or not.
"We wouldn't [have disease]. Well I don't know. If I find oysters dead like I don't know what killed them. To me it could be stress..." (*Oyster farmer*)
(4) Disease has been detected in the water body but it has not caused an issue.
"They found Marteilia refringens in Belfast. So that seems to be a buzz word at the moment. But experience with this, yeah they found it but it doesn't seem to be doing any harm to the place." (*Mussel farmer*)

Impact of disease

In the oyster sector, a disease outbreak causes rapid mortality in production.

> Well you could be sitting here next September and I could be sitting there with maybe 100,000 Euros worth of stock to sell between now and end of November or October. I could lose that in a week. That would be sad. You know. (*Oyster farmer*)

This mortality has huge economic repercussions for the shellfish production business.

> The amount of money we have sunk into that…it's just thousands, thousands. And then one year we got a disease and it wiped me out. Just when I thought I was getting it under control. I started up and had no money for about three years. I had zero. And just when I'm starting a disease came and wiped me out. Two years then I was back with very little money. And now I have got to build it up again. (*Oyster farmer*)

On the other hand, disease has not caused similar consequences to the mussel sector, despite the presence of *Marteilia refringens* in Belfast Lough and Dundrum bay.

> We have a scientist actually doing monitoring the Loughs at the moment, the Dutch authorities send him over every year…he was saying about this Marteilia refringens, he has seen it pretty much everywhere but that it doesn't seem to be something, if the water warms up, then we might have a problem with it, but in Ireland you know at current temperatures it doesn't seem to take hold. I know last year because it was a little warmer we saw it. (*Mussel farmer*)

In the disease-free areas, the shellfish farmers benefit from access to worldwide markets.

> I am Bonamia free so I can send them anywhere. (*Oyster farmers*)

Similarly, when disease is latent and not causing mortality, this provides the sector with an opportunity to capitalise on their increased production. This was particularly related to periods when disease outbreaks were causing mortalities in other production sites.

> …one year, not last year, the year before. Every other bay in Ireland had massive mortalities apart from Carlingford. So we were just selling everything and just getting top quality prices for it…They needed it and they paid for it and they paid the top dollar. (*Oyster farmer*)

However, some farmers in locations which have been declared disease-free voiced frustration over difficulties in sourcing good quality, cheaper seed from French hatcheries.

> So being a disease free bay is a problem for me. Because I can't have access to good quality seeds, the ones that grow better, the ones that are cheaper. I have to work with UK or Irish seed which comes from smaller hatcheries, with difficulties and what I got, it's not very good…the ones coming from France are coming from a selection program you know they get the best of them. So that's my problem today, I am not starting, I am not competitive I can't be competitive… (*Oyster farmer*)

Consumer perception was also discussed as a potential impact in relation to awareness and understanding of shellfish diseases. In general, stakeholders did not believe disease came under the consumers' radar.

> It doesn't really come under their radar…straight over their heads, an oyster is an oyster to them (*Oyster farmer*)

However, some explained consumers may unjustifiably associate shellfish disease as harmful to humans.

> It is not harmful to them but there is always the association, it is oyster herpes disease, I am going to eat this diseased creature. (*Oyster farmer*)

Nevertheless, the common belief was that those interested in eating shellfish will eat it and those forming negative associations are not the target consumers anyway.

> Well the world seems to be divided into two types of people. Some people who they will just not touch oysters or eat oysters or anything like that there and that is fair enough, I am not going to start going into that road…really the oyster herpes virus, it was proven that it was no risk to humans…but again there is some people who would say aww no I am not, it is like mad cow disease in cattle these things, or like the salmonella in eggs away years ago, you probably wouldn't mind that, but everything gets a rattle now and again, but there is people then who just wants to eat them and that's just the way it is, you have to go over to France or Europe, anywhere in Europe to see just how anxious, the Chinese are great customers, they will just eat everything…but someone who wants to be picky and one thing and another but in all honesty they weren't going to eat oysters anyway. (*Oyster farmer*)

Risk factors

The stakeholders in the supply chain revealed a number of risk factors they believed were related to the prevalence and intensity of disease. The purchase of imported seed from regions where a disease is prevalent was the most commonly cited route of introduction.

> …because the gigas have so many diseases in them it is starting to hit us, it has been hitting the French, now it is hitting us because it has been transported over. (*Oyster farmer*)

Similarly, stakeholders believed they are vulnerable to illegal and unregulated movements of shellfish from production areas where disease exists by other water-users into the shared water body.

> Now, you can actually go underground or go to French farmers because Native oysters or gigas oysters will reproduce there naturally in the water so they collect them and sell them and that's where disease comes from. (*Oyster farmer*)

The ploidy of the seed also played a role, with triploid believed to be more susceptible to disease.

> Triploid, yeah. But they are more susceptible to disease but they command a better price. (*Oyster farmer*).

Temperature was a significant factor important in the prevalence of a disease outbreak. For oyster herpes virus 16 °C was cited by all oyster farmers as the critical temperature threshold which activates oyster herpes virus and initiates summer mortalities.

> …oyster herpes virus doesn't help anybody and if we get water temperatures in excess of 16 degrees centigrade we can see substantial mortality here so we are not out of the woods, the further north you go the less of an impact it has because it is triggered by water temperature and that is why the French are here. (*Governing body*)

It is also believed temperature is an important factor for *Marteilia refringens*, with the current temperature regime limiting the opportunity for the pathogen to cause disease outbreaks.

> …about this Marteilia refringens…if the water warms up, then we might have a problem with it… (*Mussel farmer*)

Moreover, climate change has been cited as a risk factor for the prevalence of disease and the opportunity for new species or pathogens to survive.

> Climate change is a big one so it is at the minute we have the benefit that we are cooler than France, and if that whole thing moves up if it moves up we are going to be hit with the same diseases as France, the same prevalence of disease but are they going to get worse because they are going to get hotter they will be getting hotter than us I have caught fish in Carlingford Lough from Spain, Spanish trigger fish and that was several years ago. (*Oyster farmer*)

Although the mussel farmers did not believe the predicted two degree increase in global temperatures would be enough to cause significant concern in relation to disease.

> I don't believe two degrees in Ireland, in the water is going to cause too much problem. It could cause it elsewhere but not for the mussel industry. The oyster industry will have a huge problem with it because of the herpes virus and there is another one of those viruses but the mussels aren't susceptible to that. (*Mussel farmers*)

However, stakeholders did believe there was potential of new and emerging diseases with warmer climates and the importance of keeping the temperature below two degrees increase.

> Aww, like I said to you about the water warming up, you are learning about new diseases, it all depends, they are on about global temperatures you know, keeping them below two degrees. (*Mussel farmers*)
> The other problem now is the vibrio oyster and new disease which kill the oyster when they are commercial size which is quite a bigger problem actually than the herpes virus. (*Oyster farmer*)

Mitigation and control measures

The approaches taken for disease management and control vary, but in general, they are reactive. Some farmers did not believe there were options to help prevent disease.

> Tough luck just…if it happens it happens (*Oyster farmer*)
> …to be honest it is one of the lessons you learn about this, there is always going to be mortality because oysters have no immune system, so you can't, well there is just too many of the things, but there is nothing you can do like animals where you can spray them or dose them or anything like that there, they just die and that's that… (*Oyster farmer*)

However, others recognised the role management procedures can have in preventing the entry, spread and consequences of disease. Ensuring stress-free conditions was deemed important.

> …but what you try to do is try to make sure the conditions are right that they are happy sitting there growing. (*Oyster farmers*)

The density of production was also discussed with different stakeholders revealing conflicting views. Some farmers believed low densities helped to reduce the spread of disease.

> …with the oyster herpes virus is if the bay is low density, you know like a bay with not much production are not much affected it's like a class with many kids or a class with not many kids. If one kid gets sick in a crowded place they all get sick. And it is the same with the site. So it is all to do with the culture practice really like. (*Oyster farmer*)

Whilst others believed over-producing reduces the overall impact of a disease outbreak.

> …what you find as a response to the herpes virus mortality that people actually produce so much seed that they don't mind losing 50% of seed on the first year because what is left will keep growing until the end. You get your mortalities the first year. If you don't get it the first year you try to save it you should expose the oysters as soon as you get disease anyway so you are better off to lose them now so people use twice more seeds and lose half and the production and its back to normal. (*Oyster farmer*)

Movement restrictions and their importance in preventing the entry of disease into the waters were mentioned.

> There is a protocol in place if you are taking stuff from anywhere to put into your bed it has to be of the same disease status the water has to be the same disease status so if there is something that is in this water that you don't have you can't take that across but you can take it back. (*Oyster farmer*)

Surveillance methods are important as an early warning sign of a potential disease outbreak, particularly in areas where disease has been detected. This involves monitoring disease in the regions the seed is imported from and carrying out more rigorous inspections of the stock, particularly at times of high risk.

> We check, see if we have mortality in France after in the summer, after here check all the bag, few bag here, not each day but maybe every 15 days or sometimes when I go on the shore I check different bag to see if we start to see mortality on the oyster on. We follow that all through summer. (*Oyster farmer*)

If farmers detect any unusual mortalities, they are expected to report this to the competent authorities as a part of the disease surveillance process in the region. However, this is dependent on the adherence of the stakeholders involved.

> Like every oyster I find, I suppose you're supposed to report it but you wouldn't be bothered to be honest. If you find a dead oyster you throw it away like. You know like it could be stress or anything I don't know or something, predators. (*Oyster farmer*)

The quality of seed was also cited as an important factor for the resiliency to disease. In particular, Pacific oysters from a selection program in France were considered the most robust to oyster herpes virus.

> The key success in the farm, the quality of seed would be number one. You know if you want to do farming you have to start with nice animals, good, healthy population. If you start with oysters that have problems with growing and no resistance to disease – the ones coming from France are coming from a selection program you know they get the best of them. (*Oyster farmer*)

A common theme was the lack of reliable knowledge regarding shellfish diseases. In some cases, stakeholders voiced frustration over the overly cautious decisions made based on incomplete information and a lack of robust evidence to suggest particular diseases are a threat, e.g. *Marteilia refringens.*

> …There is another school of thought saying it is in the Foyle or it is in Belfast Lough and we can't see any damage being done just pick them out it is not doing any damage so why bother with them… (*Mussel farmer*)

However, there is risk of 'letting the genie out of the bottle' if we allow certain activities and movements without fully understanding the potential consequences.

> …but then there is other people saying if let the genie out of the bottle then it is out of the bottle you don't get it back in." (*Mussel farmer*)

Similarly, some stakeholders revealed apprehensions over the reliability and effectiveness of detection methods, surveillance and enforcement measures.

> The thing is, they consider because you cannot detect that its disease free, that there is no disease there. But I don't agree with that I think it is just because you cannot detect it not that the disease is not present. It's just your detection method may not be appropriate first or maybe because various other latent stage in the oysters can be detected because it's too difficult to detect them and that's it. (*Oyster farmer*)

Discussion

To the best of the author's knowledge, this is the first study to provide an insight into how the stakeholders involved in aquaculture production in Northern Ireland (NI) perceive disease and their experiences of it within their production system. In harmony with the literature, stakeholders involved in shellfish cultivation in NI described how the unique disease free status of the region provides opportunities to export products in the global marketplace. However, a number of shellfish diseases do exist within the region, which have undesirable consequences (DAERA 2018; Murray et al. 2012; Azrul et al. 2011).

Mollusc diseases

The shellfish diseases described by the sector included Bonamiasis, Marteiliosis and Oyster herpes virus. This reflects the status of shellfish diseases reported by the Department for Agriculture, Environment and Rural Affairs (DAERA 2018). These diseases represent only two, *Bonamia ostreae* and *Marteilia refringens*, of the seven pathogens listed in the OIE's list of notifiable diseases for shellfish. This was expected, as the remaining five are either not associated with mussel or Pacific oyster production or are not expected to survive in the environmental conditions which exist in Northern Irish waters (Table 5). Although the other pathogens were not named by stakeholders, they were aware of other potentially 'emerging' diseases under climate warming scenarios. The third pathogen, ostreid herpes virus, is not listed by the OIE. However, it has been detected throughout NI shellfish growing waters, with the exception of Larne Lough. As a result of its prevalence in NI (and throughout the UK), national measures regarding this pathogen have been set-up and approved by the EU (EC 2010a). The pathogen, particularly OsHV-1μVar, has caused similar consequences in oyster populations throughout Ireland, England, France, USA, Mexico, Australia and New Zealand in the summers of 2008 and 2009 (Murray et al. 2012; Segarra et al. 2010; Renault 2011).

Bonamia ostreae

Bonamia ostreae is a protozoan parasite that is a shellfish pathogen associated with shellfish production in Lough Foyle and Strangford Lough (DAERA 2018). Although the pathogen was identified in these areas, the stakeholders did not consider it a threat to the productivity or health of their production. However, market opportunities were restricted. This is in line with the literature that describes how the pathogen does not cause mortalities in Pacific oysters. However, the pathogen is deadly to native oysters causing mortality outbreaks in France and Ireland at temperatures of 12 °C (Azrul et al. 2011). Prevalence in infected populations can be up to 80%, and in combination with *M. refringens* it has been associated with a > 90% decline in *O. edulis* population in France (Azrul et al. 2011). Pacific oysters are thought to act as carriers and reservoirs for the disease (Lynch et al. 2010) and are on the list of vectors (EC

Table 5 Diseases listed at International and European levels (adapted from Oidtmann et al. 2011)

Diseases listed by OIE	Diseases listed by EU Directive	Susceptible molluscs
Disease exotic to EU		
Bonamia exitiosa	*Bonamia exitiosa*	Australian mud oyster (*O. angasi*) and Chilean flat oyster (*O. chilensis*)
Perkinsus marinus	*Perkinsus marinus*	Pacific oyster (*M. gigas*) and Eastern oyster (*C. virginica*)
Perkinsus olseni		
Xenhaliotis californiensis		
	Microcytos mackini	Pacific oyster (*C. gigas*), Eastern oyster (*C. virginica*), Olympia flat oyster (*O. conchaphila*) and European flat oyster (O. edulis)
Disease not exotic to EU		
Abalone herpes-like virus		
Marteilia refringens	*Marteilia refringens*	Australian mud oyster (*O. angasi*), Chilean flat oyster (*O. chilensis*), European flat oyster (*O. edulis*), Argentinian oyster (*O. puelchana*), **Blue mussel** (*M. edulis*) and Mediterranean mussel (*M. galloprovincialis*)
Bonamia ostreae	*Bonamia ostreae*	Australian mud oyster (*O. angasi*), Chilean flat oyster (*O. chilensis*), Olympia flat oyster (*O. conchaphila*), Asiatic oyster (*O. denselammellosa*), European flat oyster (*O. edulis*) and Argentinian oyster (*O. puelchana*).
Additional controls (Decision 2010/221 that enables Member states to set up national measures)		
Additional controls	Oyster herpesvirus microvariant (OsHV-1 μVar)	Pacific oyster (*M. gigas*)

2008). Thus, movement restrictions to disease free areas exist for Pacific oysters from the infected water bodies in Lough Foyle and Strangford Lough. In contrast, stakeholders involved in shellfish production in other water bodies across NI did not consider Bonamiosis as a disease threat. Instead they discussed the market opportunities it presented, allowing them to send their production anywhere throughout the world.

Marteilia refringens

Marteilia refringens is a protozoan parasite responsible for Marteiliosis disease in a wide range of shellfish including native oysters (*O. eduilis*), blue mussels (*Mytilus edulis*), Mediterranean mussels (*Mytilus galloprovincialis*) and Pacific oysters (*Magallana gigas*). The pathogen was mentioned by shellfish farmers in Belfast Lough and Dundrum Bay. However, none of the stakeholders had experienced any clinical signs or mortalities of the disease and did not believe it did any harm. It is suspected the limited activity from the pathogens is due to the typically cooler temperatures in NI and there was recognition within the sector that warming trends could potentially allow Marteiliosis to become a serious risk to both mussel and oyster production. This view is substantiated by the literature which relates mortality from the disease to water temperatures in excess of 17 °C and reduced salinities (OIE 2012; Robelo and Figueras 1995). Shellfish farmers in uninfected water bodies were not concerned by the emergence of *Martellia refringens* in Belfast Lough and Dundrum Bay. This may be due to the fact that mussel movements appear localised within one body of water and there has been no mortalities reported to date. However, with reports of 40–100% mortality rates in blue mussels and 80–90% in native and Pacific oysters in other regions (OIE 2012; Azrul et al. 2011; Murray et al. 2012) (Table 6) coupled with the market consequences of diseased bivalves (e.g. the addition of heat processing) it is important that the industry appreciates and understands the importance of mitigation measures, movement restrictions and monitoring procedures.

Ostreid herpes virus

Ostreid herpes virus was commonly reported across all stakeholders as a significant threat to the production of Pacific oysters. This is in line with the literature that has linked the most recent virulent variant of the virus, OsHV-1 μVar to extensive mortalities of Pacific oysters in Ireland since 2009 (Clegg et al. 2014; Dégremont et al. 2013; Peeler et al. 2012; EFSA 2010; Segarra et al. 2010; Malham et al. 2009). Similar mortalities have been reported throughout Europe, Australia, America and New Zealand (Renault 2011; Segarra et al. 2010). Stakeholders in NI linked these outbreaks to the importation of seed, and the large movement of spat, part grown and fully grown Pacific oysters between regions, particularly France. This is similar to other investigations of the virus in Ireland (Peeler et al. 2012). All stakeholders cited a temperature of 16 °C and above as critical for oysters and the trigger point for the virus. This supports the work by Clegg et al., (2014) who defined summer mortalities as multi-factorial, with the virus a necessary but not sufficient cause of mortality. Nevertheless, shellfish farmers in NI revealed they are at a distinct advantage in comparison to those on the continent as they believe mortality has been generally limited by the low temperatures of NI waters. However, as noted and discussed by Murray et al., (2012), diseases should not be discounted given the widespread instances of mortality observed in Ireland in the past. Other risk factors were discussed by the farmers which reinforced those illustrated in the literature: hatchery in which

Table 6 Summary of the shellfish diseases identified by stakeholders involved in shellfish cultivation in Northern Ireland

Bonamia ostreae	*Marteilia refringens*	Oyster herpes virus
Description		
° Lethal infection of the haemocytes of flat oysters, *Ostrea edulis* and the native oyster ° A lag time of 3 months is observed from introduction to detection ° Mortality in infected populations is variable, 0–90% ° Causes mortality at lower temperatures of 12 °C and at higher salinities ° No known treatment	° Protistan parasites ° Can cause mortalities in mussels (40–100%) or pacific oysters (80–90% mortality) ° Death occurs in the second year after initial infection ° Survives best at reduced salinities ° Surveillance is necessary	° Virulent disease of Pacific oysters, *Crassostrea gigas* ° Two strains exist - OsHV-1 reference strain (original) - OsHV-1 micro variant (μVar) (a mutant strain) ° Causes 'summer mortality' - Particularly in juveniles (60–80%) ° Issue in France, Ireland and England - Particularly in summers of 2008 and 2009 ° Occurs at temperatures above 16 °C
Prevalence		
° NI was disease free until 2005 when samples were positive in Lough Foyle ° Also detected in Strangford Lough ° Within the UK, prevalence is low, typically 1–3% in wild areas and 20–30% in farmed areas with relatively low levels of mortality associated with winter mortality in Ireland and France	° Detected in 2017 during routine testing in Belfast Lough and Dundrum Bay ° No clinical signs of disease ° Infected area is under confirmed designation and movement restrictions are in place	° Larne Lough is the only disease free bay ° The virus has not been detected in Dundrum Bay but it has been removed from the surveillance program due to an industry request detailing sourcing and operational difficulties ° Once established pathogen eradication may be impossible

the seed is sourced (Clegg et al. 2014). horizontal transmission of infection from unselected asymptomatic adult to juvenile *C. gigas* (Dégremont et al. 2013). increase or sudden change in temperature, husbandry practices including the introduction of possibly infected spat and the movement and mixing of population age groups, prior exposure to the virus, management practices including the age the oyster is first infected and the condition of the oysters and temperature and other environmental factors (Clegg et al. 2014; EFSA. 2010; Garcia et al. 2011). Whilst some stakeholders recognised these risk factors and the importance of implementing management strategies to ensure stress free conditions for the oyster, many were reactive and explained there were no options available to them. Moreover, the stakeholders explained there is no realistic prospect of eliminating the virus (Peeler et al. 2010); thus, legislation has been introduced to prevent the spread of the virus to unaffected areas within the UK whilst allowing trade to continue between infected areas (EC 2010a, 2010b). Larne Lough is the only waters certified as disease free and as a result they are facing difficulties in sourcing good quality, cheaper seed and believe the precautionary principle of legislation is detrimental to their business.

Impact of disease

Mollusc disease had substantial consequences to the oyster industry in the past, whilst the mussel farmers may have been protected by the temperature regime in NI. These consequences include mortality, economic loss and reputation, which have been highlighted by multiple authors on the topic of shellfish diseases (Peeler et al. 2012; Oidtmann et al. 2011). The fact that consumer's perception can affect the market was recognised by the stakeholders, particularly as the product is typically minimally processed and consumed raw or lightly cooked as a whole (Lees 2000; Murchie et al. 2005). The example of oyster herpes virus was used, whereby oyster herpes virus has proven not to be a risk to humans. However, not all consumers fully understand or accept this and if they learn of the disease association, they may 'boycott' the product. This lack of trust within consumers is a potential consequence of other scandals within the food industry, such as BSE or 'mad cow disease' in Ireland. Nevertheless, stakeholders did not believe this was a significant issue for their market of shellfish eaters. This supported the findings from Olmedo et al. (2013) who stated consumers seem to be more informed about the benefits arising from consumption of seafood rather than on the risks.

Risk of pathogens

The geographic location of the IoI was described as a key factor for the unique disease-free status of this region. In particular, the salt water barrier between Ireland and the European mainland has prevented species moving across Europe and into Ireland. Consequently, Ireland has a small number of native species in comparison to the continent and, as pathogens follow the species, the region also has a smaller number of pathogens. This unique disease-free status has enabled Ireland as a geographical unit to have substantial export trade and, any emerging diseases must find a route of introduction into the region (Murray et al. 2012).

It is therefore unsurprising that the most commonly cited introduction of disease into NI shellfish harvesting waters was the movement or import of shellfish from areas where infection was present, particularly for oyster herpes virus. This reflects the literature which defines the movement of infected hosts as the most effective way of moving pathogens (Dubé et al. 2011; Brown et al. 2006; Mortensen et al. 2006). In NI, Pacific oysters are imported from France and the UK, and thus, the sector is vulnerable to diseases which exist within these regions. The mussel sector relies on wild caught spat so there are relatively few imports of this species. However, in 2016, the Irish Supreme court ruled fishermen/farmers from NI could no longer fish for mussel-seed in their waters, a situation known as the Voisinage Arrangement (Symmons 2017). Consequently, the availability of wild spat is becoming an increasingly limited resource for mussel farmers and may lead to the use of imports to sustain current production. Stakeholders also identified other farmers and water users as a threat to their production as shellfish harvesting occurs in shared water bodies which allows other anthropogenic routes for disease entry. These potential routes have been described in the literature to include the transport of infected live aquatic animals, fomites or water; lorries that carry shellfish and aquatic species for import or export; and shipping carrying pathogens within ballast water or shellfish attached to hulls (Murray et al. 2012; Oidtmann et al. 2011). Fraud was also been highlighted as a route of introduction for disease into shellfish waters. It is believed *Bonamia* exists in Lough Foyle as a result of an illegal movement of seed from infected waters in the Western coast of Ireland; thus, other shellfish farmers suffer the consequences of the disease as a result of one farmers illegitimate activity. A significant factor cited for the prevalence of disease was temperature, particularly in terms of oyster diseases. This supports the literature which highlights the role of increasing water temperatures on disease prevalence and mortality events, particularly in relation to oyster herpes virus (EFSA 2010; Sauvage et al. 2009). Although, Garcia et al. (2011) noted OsHV-1 was often detected when temperatures rose quickly but was no longer detected once temperatures stabilise. In the mussel sector the risk of disease was not considered an issue with the current temperature regime, but trends of increasing global temperatures may active *M. refringens*. Moreover, these environmental changes associated with climate change may also create conditions which allow pathogens to survive and move naturally by water currents or wild vector species from zones of infection. However, it is more likely these changes will create increased risk from pathogens already present in the water which did not find the favourable conditions to develop in molluscs under the current temperature regime. This is supported by Salama and Murray (2011) who found the transport of shellfish species and pathogens over distance by natural routes, i.e. non anthropogenic, is unlikely.

Mitigation and control measures

Interestingly, there was a common belief among shellfish farmers' that nothing can be done to prevent a disease outbreak from pathogens which exist in the harvesting waters, it is just luck. This perception may be explained by the fact that once a disease is introduced into shellfish harvesting waters, there is often water connectivity between farmed and wild aquatic animal populations. This close interaction allows the pathogens to spread between farmed and wild aquatic animal populations. Consequently, wild populations can become a permanent reservoir of the infection and allow the pathogen to become established. The fact that disease eradication can be impossible highlights the importance of preventing any further aquatic animal diseases entering into NI harvesting waters.

At a global level, the inter-governmental body, World Organisation for Animal Health (OIE), has a mandate to improve transparency and international co-operation in the control of animal diseases, including shellfish. This body has developed two international standards for aquatic animal health: the Aquatic Animal Health Code and the Manual of Diagnostic Tests for Aquatic Animals (World Organisation for Animal Health OIE, 2010, 2011). The Aquatic Animal Health code lists the diseases which must be reported to the OIE by its members if it occurs within their territory (Table 5). This list has evolved over time and is reviewed annually. However, there are weaknesses in the time process to update the list (Murray et al. 2012; Segarra et al. 2010). The OIE standards provide generic and disease-specific guidance on how to diagnose, prevent and control these diseases (Oidtmann et al. 2011). It allows countries with a disease free status of one or more listed diseases to restrict the introduction of live susceptible species or trade in products which are not approved disease free. An important element of this biosecurity procedure involves effective surveillance for early detection. In this study, both passive and active surveillance procedures were discussed by the participants. In terms of the sensitivity of passive surveillance the stakeholders revealed there can be reluctance to report the suspicion of a disease since its detection can lead to financial and reputational loses for their business. This has been reinforced in the literature which describes how the sensitivity of the system is highly dependent on ensuring stakeholders are educated on the clinical signs of disease, allocating responsibilities and offering incentives for reporting and/or penalties for failing to report disease (Lupo et al. 2014; Oidtmann et al. 2011). The active surveillance procedures mentioned by the industry involved sampling and diagnostic testing carried out by food inspectors and government departments to confirm a disease or disease-free status and compliance to licence conditions according to EU Directive 2006/88 (EC 2006). Moreover, there are ongoing research projects on bivalve molluscs and disease. For example, the Agri-Food and Biosciences Institute (AFBI), a non-departmental public body in NI, carried out a predictive modelling study of farmed shellfish growth under temperature regimes of + 1 °C and + 4 °C as part of the Sustainable Mariculture in Lough Ecosystems (SMILE) project (Ferreira et al. 2008). The results indicated that production of mussels would decrease by 10%

and 50% under + 1°C and + 4°C scenarios respectively, whilst oysters would not experience the same extent of growth limitation under the same scenarios. If shellfish experience super-optimal thermal conditions (which is likely for intertidally cultivated species, given the predicted changes in temperature in the regions where they are cultivated) they may be more susceptible to bacterial, viral and parasitic infections (Gubbins et al. 2013). At the farm level, stakeholders outlined the strategies documented in their biosecurity plan to help prevent the introduction and spread of disease. This documented plan is a requirement of the aquaculture licence within NI which defines the acceptable standards of operation, monitoring, reporting and follow up actions for their site. It was generally accepted that good farm biosecurity can help prevent the entry of new diseases and reduce the intensity of existing disease; however, it does not guarantee disease eradication or control. A number of management practices were also highlighted; some of which were contradictory. Farming density was a topic discussed by all the stakeholders. Some thought the greater the density, the higher the risk and intensity of disease. This reinforced the findings of Murray et al. (2012) who stated a relatively low density and small scale production may reduce environmental pathogen loads and the intensity of disease in infected shellfish. Whilst others believed the key is to over produce, the weaker seed will die and what is left is strong, robust shellfish which will survive the 2-year growing period to reach a marketable size (Carlier et al. 2013). Similarly, it was voiced that the seed sourced from French hatcheries have survived prior exposure to the disease and come from a robust selective program which provides increased protection in the event of an oyster herpes disease outbreak. This thought process is similar to the results of Clegg et al. (2014) who noted a strong association between hatchery of origin and mortality. The study observed seed imported from French hatcheries displayed lower mortality compared with seed imported from non-French hatcheries, when placed in bays which were historically infected with OsHV-1μvar. This is potentially due to prior exposure to the virus (in this case OsHV-1 μVar), either of the seed itself or of the related broodstock. Other studies have noted similar results of innate immunity in bivalve species (Gestal et al. 2008; Renault 2008). Mollusc bivalves lack immunological memory; thus, the protective effect of prior exposure is not the result of a specific immune response, but likely genetic (Dégremont et al. 2007; Sauvage et al. 2009; Huvet et al. 2010) with shellfish surviving a mortality event being naturally selected for resistance to disease (Dégremont et al. 2010; Pernet et al. 2012). Stakeholders believed seed from hatcheries in France had the greatest resistance to oyster herpes disease. This reinforces Dégremont et al., (2010; 2013) who revealed the considerable progress this region has made towards the selection for OsHV-1 μVar resistant oysters, particularly in the context of summer mortality in adults. Seed ploidy was also discussed. Triploid seeds were believed to be of better quality and more robust for cultivation, which supports the observations of Clegg et al. (2014), Samain (2011) and Gagnarie et al. (2006), but is contradictory to an Irish study carried out by Peeler et al. (2012). A more robust research design is required to confirm which seed has a greater resistance to disease as different co-founding factors were not accounted for or controlled in these studies.

Conclusion

The study provided a unique insight into the stakeholder's perspective of mortality events affecting farmed shellfish production in Northern Ireland. The rich descriptive data retrieved highlighted the vulnerability of the sector and the uncertainties it faces as a result of disease.

The diseases cited included Bonamiasis in Lough Foyle and Strangford Lough, Marteiliosis in Belfast Lough and Dundrum Bay and oyster herpes virus disease across NI's coastal loughs, with the exception of Lough Foyle. However, the only disease noted to cause significant mortalities and a concern for shellfish farmers was due to oyster herpes virus. Worryingly, the continuation of warming trends could make the environment more conductive to shellfish disease outbreaks, particularly Marteiliosis and oyster herpesvirus disease. This warming may also provide opportunities for new pathogens to become established or present but non virulent pathogens to find favourable conditions for their development in molluscs. The outbreak of a disease is multi-factorial with stakeholders naming temperature, hatchery source and cultural operations as key risk factors associated with resiliency and disease mortality. However, further research is necessary to clarify the effect each of these factors play and others which may exist. Effective biosecurity measures are essential to prevent the expansion of localised diseases and the introduction of new diseases. In general, the current mitigation and control of disease are reactive and based on active and passive surveillance of pathogens. There needs to be a cultural shift to disease appreciation. Proactive disease prevention and control are crucial to eradicate and control disease and maintain a sustainable shellfish farming industry in this region. This should include risk analysis of current and emerging diseases coupled with economically viable and effective surveillance and mitigation measures. Research, education, training and collaboration are essential to ensure aquaculturists understand and appreciate the risk of disease and are equipped with quick, robust and economically efficient mitigation options and the skills to utilise them. This will prove increasingly important as the industry faces issues associated with increased risk of disease, e.g. climate change and intensified production systems. It is important that each member state carries out a similar qualitative study in order to understand the level of understanding and compliance of shellfish farmers to the active and passive surveillance systems in place and their role in helping to reduce the impact on disease on the overall productivity and profitability of the sector. Such studies may help to inform the EU about the need to update EU regulations or provide some flexibility for a better harmonisation of shellfish disease prevention and control through EU.

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Compliance with ethical standards

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References

AFSB. (2013). *Going for growth. A strategic plan in support of the Northern Ireland Agri-Food Industry.* [online] Belfast: Agri-Food Strategy Board, pp.1-85. Available at: https://www.daera-ni.gov.uk/sites/default/files/publications/dard/going-for-growth.pdf [Accessed 4 Oct. 2018].

Azrul I, Langlade A, Chollet B, Robert M, Ferrand S, Omnes E, Lerond S, Couraleau Y, Joly JP, François C, Garcia C (2011) Can the protozoan parasite Bonamia ostreae infect larvae of flat oysters *Ostrea edulis*? *Vet Parasitol* 179:69–76

BBC News. (2016) *Oyster farms cashing in on politics dispute.* [online] Available at: https://www.bbc.co.uk/news/uk-northern-ireland-38256155 [Accessed 30 May 2018].

Brown JH, McLeod DA and Scott DCB (2006) *Development of best practice in relation to movement of bivalve shellfish stock. Report of Project No FC1017/CSA7049*, commissioned by DEFRA, pp. 68.

Carlier M, Prou J, Mille D and Lupo C (2013) Oyster farmers' perception of spat mortality outbreaks: more a firm than a farm issue. *Society for Veterinary Epidemiology and Preventive Medicine*. Proceedings of a meeting held in Madrid, Spain, 20–22 March 2013, pp. 226–237

Clegg TA, Morrissey T, Geoghegan F, Martin SW, Lysons K, Ashe S, More SJ (2014) Risk factors associated with increased mortality of farmed Pacific oysters in Ireland in 2011. Prevent Vet Med 113:257–267

Cressey D (2009) Aquaculture: Future fish. *Nature* 458:398–400

DAERA (2018) *Introduction to aquaculture | Department of Agriculture, Environment and Rural Affairs.* [online] Available at: https://www.daera-ni.gov.uk/articles/introduction-aquaculture [Accessed 18 May 2018].

Degremont L, Boudry B, Ropert M, Samain JF, Bedier E, Soletchnik P (2010) Effects of age and environment on survival of summer mortality by two selected groups of Pacific oyster *Crassostrea gigas*. Aquaculture 299:44–50

Degremont L, Ernande B, Bedier E, Boudry P (2007) Summer mortality of hatchery produced Pacific oyster spat (Crassostrea gigas). An estimation of genetic parameters for survival and growth. Aquaculture 262:41–53

Degremont L, Guyader T, Pepin JF (2013) Is horizontal transmission of the Ostreid herpesvirus OsHV-1 in *Crassostrea gigas* affected by unselected or selected survival status in adult juveniles. Aquaculture 408:51–57

Dube C, Ribble C, Kelton D, McNab B (2011) Introduction to network analysis and its implications for animal disease modelling. *Rev Sci Tech* 30:425–4436

EC (2006) Council Directive 2006/88/EC of 24 October 2006 on animal health requirements for aquaculture animals and products thereof, and on the prevention and control of certain diseases in aquatic animals. Off J Eur Union L328:14–56

EC (2008) Commission regulation (EC) No 1251/2008 of 12 December 2008 implementing Council Directive 2006/88/EC as regards conditions and certification requirements for placing on the market and the import into the Community of aquaculture animals and products thereof and laying down a list of vector species. Off J Eur Union L337:41–75

EC. (2009) Communication from the Commission to the European Parliament and Council. *Building a sustainable future for aquaculture. A new impetus for the Strategy for the Sustainable Development of European Aquaculture. COM* (2009) 162 final.

EC (2010a) Commission regulation (EU) No 178/2010 of 2 March 2010 implementing Council Directive 2006/88/EC as regards measures to control increased mortality in oysters of the species *Crassostrea gigas* in connection with the detection of Ostreid herpesvirus I μVar (OsHV-1 μVar). Off J Eur Union L328:13–27

EC (2010b) Commission decision of 15 April 2010 approving national measures for limiting the impact of certain diseases in aquaculture animals and wild aquatic animals in accordance with Article 43 of Council Directive 2006/88/EC. Off J Eur Union, L98/, pp. 7-11.

EFSA (2010) Scientific opinion on the increased mortality events in Pacific oysters, *Crassostrea gigas. EFSA Journal*, 8, pp. 1894.

FAO. (2018) *The state of world fisheries and aquaculture 2018—meeting the sustainable development goals.* [online] Rome: Food and Agriculture Organisation of the United Nations, pp. 1-227. Available at:

http://www.fao.org/3/i9540en/I9540EN.pdf?segid=0876d2c2-ec76-44e0-9405-55de70116ecb [Accessed 20 April 2019].

Ferreira JG, Hawkins AJS, Monteiro P, Service M, Pascoe PL, Ramos L, Sequeira A (2008) Integrated assessment of ecosystem-scale carrying capacity in shellfish growing areas. *Aquaculture* 275:138–151

Gagnarie B, Soletchnik P, Madec P, Geairon P, Le Moine O, Renault T (2006) Diploid and triploid Pacific oysters, *Cassostrea gigas* (Thunberg), reared at two heights above sediment in Marennes-Oleron Basin, France: difference in mortality, sexual maturation and hemocyte parameters. Aquaculture 254:606–616

Garcia C, Thebault A, Degremont L, Arzul I, Miossec L, Robery M, Chollet B, Francois C, Joly JP, Ferrand S, Kerdudou N, Renault T (2011) Ostreid herpesvirus 1 detection and relationship with *Crassistrea gigas* spat mortality in France between 1998 and 2006. *Vet Rec* 42:73

Gestal C, Roch P, Renault T, Pallavicini A, Paillard C, Nova B, Oubella R, Venier P, Figueras A (2008) Study of diseases and the immune system of bivalves using molecular biology and genomics. *Rev Fish Sci* 16:133–156

Gubbins M, Bricknell I and Service M (2013) Impacts of climate change on aquaculture. *Marine climate change impacts partnership: Scientific Review,* pp. 318-327.

Huvet A, Normand J, Fleury E, Quillien V, Fabioux C, Boudry P (2010) Reproductive effort of Pacific oysters: a trait associated with susceptibility to summer mortality. Aquaculture 304:95–99

Jayasinghe RPPK, Amarasinghe US, Newton A (2016) Evaluation of status of commercial fish stocks in European marine subareas using mean trophic levels of fish landings and spawning stock biomass. Ocean Coastal Manag 143:1–10

Jennings S, Stentiford GD, Leocadio AM, Jeffery KR, Metcalfe JD, Katisadaki I et al (2016) Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment. Fish Fish 1:1–46

Lauria V, Das I, Hazra S, Cazcarro I, Arto I, Kay S, Ofori-Danson P, Ahmed M et al (2018) Importance of fisheries for food security across three climate change vulnerable deltas. *Sci Total Environ* 640-641:1566–1577

Lees D (2000) Viruses and bivalve shellfish. Int J Food Microbiol 59:81–116

Lupo C, Osta Amigo A, Mandard YV, Peroz C, Renault T (2014) Improving early detection of exotic or emergent oyster diseases in France: Identifying factors associated with shellfish farmer reporting behaviour of oyster mortality. Prevent Vet Med 116:168–182

Lynch SA, Abollo E, Ramilo A, Cao A, Culloty SC, Villalba A (2010) Observations raise the question if the Pacific oyster, *Crassostrea gigas*, can act as either a carrier or a reservoir for *Bonamia ostreae* or *Bonamia exitiosa*. Parasitology 137:1515–1526

Malham SK, Cotter E, O'Keeffe S, Lynch S, Culloty SC, King JW, Latchford JW, Beaumont AR (2009) Summer mortality of the Pacific oyster, *Crassostrea gigas,* in the Irish Sea: the influence of temperature and nutrients on health and survival. Aquaculture 287:128–138

Marquis ND, Record NR, Fernández-Robeldo JA (2015) Survey for protozoan parasites in Eastern oysters (*Crassostrea virginica*) from the Gulf of Maine using PCR-based assays. Parasitol Int 64:299–302

Mortensen S, Korsnes K, Bergh Ø (2006) "Eyes wide shut". A critical view of aquaculture health management and risk factors in the "real world". B Eur Assoc Fish Pat 26:1–5

Murchie LW, Cruz-Romero M, Kerry JP, Linton M, Patterson MF, Smiddy M et al (2005) High pressure processing of shellfish: a review of microbiological and other quality aspects. Innov Food Sci Emerg 6(3):257–270

Murray AG, Marcos-Lopez M, Collet B, Munro L (2012) A review of the risk posed to Scottish mollusc aquaculture from Bonamia, Marteilia and oyster herpesvirus. Aquaculture 370-371(11):7–13

Oidtmann BC, Thrush MA, Denham KL, Peeler EJ (2011) International and national biosecurity strategies in aquatic animal health. Aquaculture 1-2(19):22–33

OIE (2012) *Manual of Diagnostic Tests for Aquatic Animals 2012*. [online] Paris: World Organisation for Animal Health. Available at: http://www.oie.int/international-standard-setting/aquatic-manual/access-online/ [Accessed 30 May 2018].

Olmedo P, Pla A, Hernández AF, Barbier F, Ayouni L, Gil F (2013) Determination of toxic elements (mercury, cadmium, lead, tin and arsenic) in fish and shellfish samples. Risk assessment for the consumers. Environ Int 59:63–72

Peeler EJ, Reese RA, Thrush MA (2010) Report on investigation of oyster herpes virus infection and oyster mortality in the Republic of Ireland in 2009 – A questionnaire Survey. Centre for Environment, Fisheries and Aquaculture Science (Cefas), Weymonth.

Peeler EJ, Reese RA, Cheslett DL, Geoghegan F, Power A, Thrush MA (2012) Investigation of mortality in Pacific oysters associated with ostreid herpesvirus-1 μvar in the Republic of Ireland in 2009. Preventative Veterinary Medicine 105:136–143

Pernet F, Barret J, Le Gall P, Corporeau C, Dégremont L, Lagarde F, Pepin JF, Keck N (2012) Mass mortalities of Pacific oysters *Crassostrea gigas* reflect infectious diseases and vary with farming practices in the Mediterranean Thau lagoon, France. Aqua Environ Interact 2:215–237

Renault TC (2008) Genomics and mollusc pathogens: trends and perspective. *J Vet Sci* 1:36–46

Renault TC (2011) Viruses infecting marine molluscs. In: *Studies in Viral Ecology (Vol 2):,* 1st ed. NJ: Wiley-Blackwell Hoboken, pp. 153-172.

Robelo JAF, Figueras A (1995) The effects of culture-site, depth, season and stock source on the prevalence of *Marteilia refringens* in cultured mussels (*Mytilus galloprovincialis* LMK) from Galicia, Spain. J Parasitol 81:354–363

Salama NKG, Murray AG (2011) Farm size as a factor in hydrodynamic transmission of pathogens in aquaculture fish production. Aqua Environ Inter 2:61–74

Samain JF (2011) Review and perspectives of physiological mechanisms underlying genetically based resistance of the Pacific oyster *Crassostrea gigas* to summer mortality. Aqua Living Resour 24:227–236

Sauvage C, Pepin JF, Lapègue S, Boudry P, Renault T (2009) Ostreid herpes virus 1 infection in families of the Pacific oyster, *Crassostrea gigas,* during a summer mortality outbreak: differences in viral DNA detection and quantification using real-time PCR. Virus Res 142:181–187

Segarra A, Pepin FJ, Arzul I, Morga B, Faury N, Renault T (2010) Detection and description of a particular ostreid herpesvirus 1 genotype associated with massive mortality outbreaks of Pacific oysters *Crassostrea gigas*, in France in 2008. Virus Res 153:92–99

Symmons CR (2017) Recent Developments in Ireland: The Voisinage Doctrine and Irish Waters: Recent Judicial and Legislative Developments. Ocean Dev Int Law 49(1):79–84

United Nations (2017) *World Population Prospects: The 2017 Revision*. United Nations, New York

Waite, R., Beveridge, M., Brummett, R., Castine, S., Chaiyawannakarn, N., Kaushik, S., Mungkung, R., Nawapakpilai, S., Phillips, M. (2014) Improving productivity and environmental performance of aquaculture. In: Institute W.R. (Ed.), *Creating a Sustainable Food Future,* pp. 1-49. World Resources Institute, Washington, DC.

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