WORKSHOP ON EMERGING MOLLUSC PATHOGENS (WKEMOP)

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i Executive summary

Emerging pathogens threaten aquaculture industries worldwide. There is urgency to become better prepared and meet these challenges, as aquaculture is growing rapidly and will contribute increasingly to food security. There are important Pacific oyster production areas *today* as yet unchallenged by emergent OsHV-1 microvariants, notably in the Americas, and to these areas the viruses are an immediate threat.

The ICES Workshop on Emerging Mollusc Pathogens addressed fundamental questions regarding capabilities (expertise, infrastructure) and communication (among the pathology community, regulation, and industry). We sought to identify areas warranting investment and support to manage emerging diseases in shellfish aquaculture industries, and to provide justification for resources to be directed to these areas for more effective management of shellfish health. Thirty-six priorities were identified spanning four areas: i) *improving communication and frameworks*; ii) *essential infrastructure and expertise*; iii) *key research priorities*; and iv) *the central role of husbandry* in shellfish aquaculture health management. *Improving communication* in every regard was recognized as the greatest need. Better coordinating efforts, improving data sharing, and improving trust on the part of industry to create buy-in and improve reporting were among identified priorities. Regulatory frameworks were recognized as needing to be flexible, given the often urgent need to act with incomplete information when a disease emerges.

For *essential infrastructure and expertise* the workshop emphasized the continued importance of traditional fields such as pathology, bacteriology and virology, which remain foundational to aquaculture health management. Maintaining laboratory capacity is critical, in distribution as well as technologically: there is value in maintaining not just national or pan-national laboratories but provincial governmental and academic labs too, which can be more intimately engaged with local producers, and familiar with local environments. Disease challenge models and facilities were additionally identified as essential for testing hypotheses, as was expertise in epidemiology, which is sharply limited for marine systems.

Discussion of *key research priorities* highlighted the value of long-term studies for understanding infection patterns; for appreciating dynamics like resistance and tolerance evolution versus virulence evolution; and for understanding effects of changing environments. The importance of improving ecological and evolutionary perspective in general was emphasized, as was the need to develop strategies for monitoring the diversity of potential pathogens. Establishment of molluscan cell lines for viral work would be a particularly valuable tool.

Aquatic animal husbandry offers myriad opportunities to control pathogens. Understanding intersections of disease with aquaculture production for different host-pathogen systems requires continued research investment. Focused investment is also required to pursue strategies emerging from this research, including disease resistance breeding. Tighter collaboration among practical aquaculture scientists and breeders and pathologists should be promoted.

Finally, *funding* was recognised as a continuing challenge. Priorities of donors and funding agencies do not always match commercial and health management priorities; basic surveillance is a key area difficult to support. Short funding timelines challenge our ability to address key questions and challenges, including breeding to control diseases. And there is little funding for truly trans-national, collaborative research. Managing diseases to support aquaculture growth is a global problem that demands science that is equally global, which requires the capacity to build broad international collaborations. It would be immensely beneficial for sustainable aquaculture development if trans-national research initiatives in aquatic animal health and other aquaculture related fields could be established to support innovation in this area in the future.

ii Expert group information

Expert group name	Workshop on Emerging Mollusc Pathogens (WKEMOP)
Expert group cycle	Annual
Year cycle started	2019
Reporting year in cycle	1/1
Chair(s)	Janet Whaley, USA
	Ryan Carnegie, USA
Meeting venue(s) and dates	6-7 June 2019, Copenhagen, Denmark (16 participants)

1 Introduction

Emerging pathogens represent one of the most significant threats to the growth and sustainability of aquaculture industries worldwide. In the realm of mollusc aquaculture, there is a long history of emerging diseases devastating harvested molluscan shellfish populations, with effects often altering ecosystems, sometimes permanently. The emergence of *Haplosporidium nelsoni* in the 1950s and intensification of perkinsosis caused by *Perkinsus marinus* along the Atlantic coast of North America in the 1980s (Burreson and Andrews 1988), for example, effectively abolished a century-old oyster planting industry that had existed in the Chesapeake Bay, and contributed to a permanent shift in that system from benthic- to pelagic-dominated production (Kemp et al. 2005). In Europe, emergence of iridoviral disease in the Portuguese oyster in the 1960s drove that species to commercial extinction (Comps 1969, Grizel and Héral 1991), and was closely followed by catastrophic disease outbreaks caused by *Marteilia refringens* (Grizel et al. 1974) and *Bonamia ostreae* (Pichot et al. 1980) that crippled flat oyster industries. These events provided the impetus for the massive introduction to Europe of Pacific oyster *Crassostrea gigas* from Canada and Asia, with far reaching effects for the European shellfish aquaculture industry and coastal ecosystems more generally.

More recently, a "microvar" variant of the ostreid herpesvirus OsHV-1 emerged in France in 2008 causing sharply elevated disease and mortality in farmed Pacific oysters. This local emergence of a new variant occurred against a backdrop of "reference strain" OsHV-1 being distributed more broadly world-wide, including in Europe and in Pacific oysters in Mexico and two California locations. It was subsequently followed by outbreaks caused by other OsHV-1 microvariants in Pacific oysters in New Zealand and Australia beginning in 2010, also causing significant damage to industries there. In Europe, the virus was quickly recognized as distinct from existing European strains (Segarra et al. 2010) and as a "necessary cause" of the mortality (EFSA 2010), yet it was not adequately controlled and rapidly spread through most Pacific oyster growing areas in Europe. Part of the reason for this was the concurrent detection of *Vibrio* pathogens, which produced uncertainty as to cause of the mortality; coming to terms with the diversity of *Vibrio* pathogens affecting shellfish and their contributions to disease, in Europe as well as in North America, Australia and elsewhere, in fact remains a challenge and the focus of intensive study.

Our collective experience as a community of aquatic animal health scientists and professionals with the OsHV-1 microvariant emergence in particular raises questions about our preparedness to manage emerging disease threats. The challenges we have faced with viral as well as bacterial detection and characterisation, and in understanding the contributions of these pathogens to disease and their broader ecology, highlight the challenges we face in dealing with viral and bacterial pathogens in particular, as a mollusc health community that to a significant extent has historically concerned itself with protozoan parasites. There is an urgency to our readiness and meeting these challenges. Aquaculture is growing rapidly in the ICES region and elsewhere, and marine aquaculture will contribute increasingly and essentially to food and nutritional security of growing human populations in the coming years. Bivalve mollusc aquaculture is a particularly important element of this given its low carbon footprint and sustainability (Hilborn et al. 2018). More immediately, we must recognize that *today* there are important Pacific oyster production areas as yet unchallenged by the emergent OsHV-1 microvariants, notably in the Americas, and that for these populations and production areas these emerging viruses represent a grave contemporary threat.

With this context in mind, we convened an ICES Workshop on Emerging Mollusc Pathogens on 6-7 June 2019, in Copenhagen and with sixteen participants from Denmark, France, Germany, Iceland, Ireland, Norway, Spain, the USA, New Zealand, Australia, and the World Organisation for Animal Health (OIE), to address fundamental questions in two broad areas. First, with regard to capabilities, *do we have the expertise we need, in the right places with regard to our national and international aquatic animal health management infrastructures, to effectively detect and manage emerging mollusc pathogens (EMOPs)?* What is this expertise, especially with regard to viral and bacterial pathogens and their ecology and epidemiology? What are essential tools, platforms, and capabilities do we need to have at our disposal? Do we need other tools, platforms, and capabilities to *understand* these pathogens? What questions do we need to be prepared to ask in terms of advancing essential science to inform management? And second, with regard to communication, *is communication adequate within the pathology community? Is it adequate among the pathology community, regulators and policy makers, and the private sector? Is it adequate between academic and research institutions and national veterinary labs?* Where, and how, do we fall short? How might this be improved? What would a framework for improved future response to EMOPs look like?

Our goal was to identify areas warranting investment and support, development and improvement as we consider managing emerging diseases against the backdrop of growing shellfish aquaculture industries; and to articulate compelling justification for ICES member countries and others to direct resources to these areas as appropriate, for more effective management of shellfish health moving forward. A proximate motivation behind this workshop was the US concern about emerging mollusc pathogens, specifically the OsHV-1 microvariants, that could adversely affect US shellfish aquaculture production; this is reflected in the financial support for the workshop, which was provided by the US Department of State, and National Oceanographic and Atmospheric Administration (NOAA). Uncovering what we might learn from the decade of experience with OsHV-1 microvariants in Europe, New Zealand, and Australia with regard to preventing introduction to new areas, and effectively mitigating effects where the virus does occur — what has worked, what has not — is a keen North American interest. It is also an important objective of broader ICES Working Group of Pathology and Diseases of Marine Organisms (WGPDMO) activities under which the WKEMOP resides. More broadly, however, we recognize a need to prepare to detect and manage emerging mollusc pathogens from whichever taxon they emerge, as history has shown they inevitably will.

Finally, we emphasize that the WKEMOP was only a starting point for a broader discussion. For one thing, the attendance was limited: necessarily because of funding limitations, but specifically and deliberately to primarily represent the pathology community. The intent of this workshop was to primarily generate a "grass-roots" perspective from the research and diagnostic professionals closest to the science and to industry, and most keenly aware of limitations at this level. Expansion of the discussion to broader spheres, including the regulatory community and competent authorities charged with maintaining the biosecurity of aquaculture commerce at higher levels, has already been initiated by virtue of valuable participation in the WKEMOP by the OIE, which had the additional benefit of opening collaboration in aquaculture health between ICES and the OIE. Further dialogue with the regulatory community among the ICES countries as well as with industry to more sharply define a path forward, including an effective framework for coordinating international responses to emerging marine diseases, will be forthcoming.

2 Opening discussions: the OIE, and experiences with OsHV-1 microvariants in Europe, New Zealand and Australia

WKEMOP began with an initial presentation by Gillian Mylrea (OIE). Mylrea provided historical perspective on the OIE and underscored the alignment of OIE interests and objectives with those of ICES in promoting sustainable aquaculture industries and the health of aquatic animals. She spoke to the core OIE missions of maintaining standards for pathogen prevention, detection and control, maintaining transparency with regard to disease status of the 182 member countries, and promoting competence in veterinary services and the ability to implement standards. The OIE has a list of seven notifiable mollusc diseases (infection with abalone herpesvirus, *Bonamia exitiosa*, *B. ostreae*, *M. refringens*, *Perkinsus olseni, P. marinus*, and *Xenohaliotis californiensis*), and a main aim is to prevent transboundary spread of these diseases. Prompt detection and reporting, implementation of standards, and promotion of husbandry practices that maximize animal health and biosecurity are ingredients for success. Mylrea noted an agreement from 2007 between the OIE and ICES to build collaboration, and expressed an OIE desire to see this develop momentum.

Discussion commenced with a question about listing and reporting of pathogens, which Mylrea acknowledged remains a challenge because of political implications. There is a reluctance on the part of OIE member countries to list new pathogens and to report pathogens that are listed because of the potential impacts on exports. Criteria for listing of pathogens include that "a precise case definition is available and a reliable means of detection and diagnosis exists" (OIE 2018), but development of reliable diagnostics in particular takes time, and listing may be impossible to justify based on other criteria (such as the pathogen being limited in distribution) by the time suitable diagnostic assays are developed.

The point was made that "emerging diseases" can represent not only newly discovered pathogens, but changes in established pathogens (the example of the intensification of *Perkinsus marinus* in eastern oysters in the USA in the 1980s [Burreson and Andrews 1988] would here apply), and also the emergence of new pathogen strains, as was the case with the OsHV-1 microvariants that emerged in Europe, New Zealand and Australia and *Vibrios* that emerged in recent years in Europe. Defining "precise case definitions" where sub-specific or strain-level pathogen diversity may be relevant to listing and control represents a great challenge.

A second presentation by WKEMOP co-chair Ryan Carnegie (USA) introduced the WKEMOP objectives and agenda. He introduced some of the US backdrop that served as motivation for the WKEMOP, including substantial aquaculture production of oysters (Pacific oysters, 41K tons, worth $75M USD; eastern oysters, 118K tons worth $148M USD) as well as quahog clams (23M tons worth $78M USD) and Manila clams (4.7K tons, $26M USD) (all figures from www.fao.org), all presently with freedom from OsHV-1 microvariant impacts. He also expressed the need to better identify, understand, and manage a range of risks and vulnerabilities related to this production, including inconsistent or limited availability of hatchery seed compelling growers to obtain seed from distant sources; a limited number of established pathology laboratories to engage the industry; only modest systematic disease surveillance with regard to farms or surrounding wild shellfish populations; little coordination and information sharing among the states and federal government; and lack of funding and other resources for shellfish health and marine disease diagnostics and research generally.

Carnegie's presentation was followed by presentations by Isabelle Arzul (France), Zoë Hilton (New Zealand), and Peter Kirkland (Australia) to offer perspective from experiences with OsHV-1 microvariants and other pathogens in Europe, New Zealand and Australia. This recent experience, and perception of what was successful and what was not in terms of responses to the outbreaks, should inform our approach to emerging pathogens moving forward.

In Europe, as described in the presentation by Isabelle Arzul, the initial focus following OsHV-1 microvar emergence in France was on prevention of introduction via seed transfers at the country level, which allowed the United Kingdom and Ireland to initially remain free. This was made difficult, however, by the fact that OsHV-1 microvar was not a listed pathogen, and the pathogen was able to spread through most Pacific oyster growing areas in Europe; the limited geographic distribution of seed sources (hatcheries, wild seed collection sites, both primarily in France) represented a production bottleneck that contributed to pathogen spread. It was also the case that the onus was on non-affected areas (such the UK and Ireland) to demonstrate freedom from infection for transfer restrictions to be justified; the default was the open flow of seed. Having appropriate data on hand to offer proof of disease freedom, or being able to quickly mobilise the resources to generate such data, is a substantial challenge. In Australia, it was noted, the converse is the case: the burden is on source areas to demonstrate safety of product, a more precautionary approach.

Arzul reflected considerably on surveillance, and the need to improve in this area. Active and passive surveillance should be combined with broad geographic and species coverage, but active surveillance is particularly costly. Tools and approaches should be adapted to the circumstances. Mortality may not be the best "marker" to trigger passive surveillance, but what would be a suitable marker is a question that would need to answered with research. For specific pathogens, we need to determine which surveillance and diagnostic approaches are best. For all species, surveillance and diagnostic tools should be improved and competence of laboratories should be ensured. Disease management in general is difficult, Arzul noted, and success will require better integration of laboratories and scientists, with competent authorities at the table. Suitable management may be very local in terms of management and engagement with industry: what is preferred, what is tolerable, and so on.

Arzul also presented on the European VIVALDI project, including the myriad research fronts active under this umbrella. Particularly noteworthy among the research Arzul highlighted was the protection of Pacific oyster spat from OsHV-1 provided by co-cultured organisms such as ascidians. The interactions of other species with host-pathogen dynamics, including those that might be modulated through microbiome interactions, are a ripe area for research for potential applications to farm-level disease management. A primary aim of VIVALDI is to build a network of mollusc pathology professionals extending beyond Europe, which would have immense value to the field.

Discussion following the Arzul presentation covered several topics. Bacterial pathogens such as *V. aestuarianus* are contributing materially to disease and mortality in oyster populations in Europe, including marketable oysters in the case of *V. aestuarianus*, which we are still working to get a grasp of. Many labs are running specific molecular assays but few are doing more basic plating, which Arzul believes is essential for broader understanding of the suite of bacterial pathogens that may be present. Other disease issues such as neoplasias and "summer mortality" were raised, as examples that present contemporary challenges. Neoplasias will be more challenging to address with regard to resolution of etiology, whether transmissible or not, and to detection. Summer mortality may relate to one or another known pathogen, or other host or environmental factors. Both neoplasias and summer mortality may be relevant to management but challenge the establishment of case definitions and suitable diagnostic assays.

“Re-soaking” or “re-swimming”, the temporary wet storage of product ready for sale or consumption, was noted as being common in Europe to freshen animals prior to consumption. There was considerable sentiment among European participants that this activity is widespread enough to present a substantial risk with regard to pathogen introductions as well as introductions of “hitch-hiking” organisms. Recent discussions in the US on the topic, related to proposed introductions of market oysters from Europe, have in some cases discounted the threat posed by re-soaking, based on the assumption that it is not common in the US. This may not be correct. The question was raised as to whether wild-caught animals temporarily wet-stored were truly “aquacultured”? There is clearly a wide spectrum of activities, such as containment, or control of the host life cycle and genetics, in bivalve mollusc culture. The important point is that blind spots must not be created with regard to disease management based on nuances in the definition of “aquaculture”.

On a final note of discussion following the Arzul presentation, the question was raised of virulence evolution in pathogens: is virulence evolution greater (toward higher virulence) in aquaculture scenarios, as pathogens adapt for example to host resistance, or to host removal before transmission can be effected? This question highlights the importance of evolutionary epidemiological framing of research on aquaculture health. With regard to the specific question, it also highlights the potentially usefulness of viewing and managing diseases of cultured molluscs in a holistic, ecosystem sense. Wild Pacific oysters in an ecosystem with a high diversity of other organisms, for example, may present a different selective environment with regard to pathogen evolution than would Pacific oysters on an oyster farm; aquaculture is theoretically more likely to select for more virulent pathogens because of compression of the rearing cycle (Kennedy et al. 2016). In general, the biocenosis of a farm environment would typically diverge from that of a natural system, with implications for both the ecology and evolution of diseases.

The next presentation by Zoë Hilton provided perspective on the New Zealand experience with OsHV-1 microvariants. The initial outbreak in 2010 produced very high mortality (> 90%) in young Pacific oysters, particularly in North Island growing areas where the bulk of the country’s production occurred. There was no coordinated reporting from industry at this time, and affected parties in the industry were unaware of the cause of mortality and assumed it due to environmental causes. Therefore the movement of seed and stocks to other areas continued as usual and spread the virus widely.

The very rapid spread of the virus throughout the entire range of growing areas over the first two years made it too late for broad restrictions on oyster transfers to be justified, once the extent of the virus impacts was reported, so no industry-wide strategies were developed for viral control. Industry rapidly engaged in a very robust breeding programme for resistance to OsHV-1 in collaboration with the private Cawthron Institute, which already had an existing breeding programme for Pacific oysters. This, of course, mirrored the focussed breeding for OsHV-1 microvar resistance conducted in Europe, specifically in French hatcheries. The funding for breeding work in New Zealand was via a six-year grant, a long funding window relative to the US in particular, but ideal for selective breeding as the support window enabled the production of three oyster generations – proving the utility of the process, and allowing the industry to recover sufficiently to take over funding the breeding programme themselves, as has now happened.

The New Zealand approach to breeding for OsHV-1 microvariant resistance, it should be noted, was different than the approach in Europe, particularly in French hatcheries, both in philosophy and implementation. It was able to be rapidly and broadly implemented, however, with commercial numbers of selectively bred spat available for use by 2013. An exploration of the merits (and success) of different approaches to breeding for resistance to emerging pathogens, for industries of different structures and scales, should be a priority as a follow-up to the WKEMOP, and we will be engaging the Working Group on Application of Genetics in Fisheries and Aquaculture (WGAGFA) in pursuing this.

Hilton noted that New Zealand oyster production is doing well, although still lower than pre-outbreak production, by virtue of the progress in breeding for OsHV-1 microvariant resistance; and that although the industry is earning more than in pre-outbreak times due to increases in price, the industry has consolidated into many fewer, larger producers because of the outbreaks, with smaller producers not having had the resources and resilience to withstand the initial years of the outbreak. A similar contraction of the industry, with loss of smaller, less deeply resourced companies, has been reported in France (Marine Fuhrmann presentation, OIE Global Conference on Aquatic Animal Health in Santiago, Chile).

Discussion following the Hilton presentation focussed on some of the nuance inherent in oyster-OsHV-1 microvariant systems. Isabelle Arzul noted that in Europe there is a diversity of OsHV-1 microvariants that can be detected, the significance of which is not clear. Diversification and evolution of viral lineages would be an important area to gain more insight into. Arzul also noted that European Pacific oyster populations show both resistance and tolerance adaptations to the viruses, and that the age-specific infection profile – the virus typically infecting small seed – does not hold well when oysters are co-infected by *Vibrio* bacteria. In co-infections, larger and older oysters can be more seriously affected by OsHV-1. This latter observation has relevance to our understanding of OsHV-1 epizootiology and to strategies for control.

Finally, a question was raised concerning the scale of the Cawthron breeding programme for OsHV-1 resistance. As the NZ production of Pacific oysters is relatively small compared to larger countries, a single breeding programme is able to provide selectively bred spat to a large proportion of the national industry, therefore significantly facilitating the recovery of the industry at a national scale. In addition, efforts have been made to supply spat in a format that is accessible to different methods of growout to make the selective breeding gains available to all parts of the industry. It was discussed that in larger countries such as France, selective breeding approaches had been more fragmented, and in large countries such as the US, it may be necessary to have a coordinated approach at state and federal level to implement breeding programmes and associated hatchery supply to fulfil such a large need over such large geographical areas.

The final presentation by Peter Kirkland presented the Australian situation, highlighting perspective either particularly unique or particularly reinforcing vis-à-vis the earlier presentations by Arzul and Hilton. Kirkland highlighted the genuine biosecurity of Australia afforded by its geographic isolation – which New Zealand shares – and suggested that it was probably ballast water or another ship vector that brought the OsHV-1 microvariants to Australia, possible from Asia where a diversity of OsHV-1 strains occur (Mineur et al. 2015).

Outbreaks of OsHV-1 microvariant-caused disease were devastating to Pacific oyster industry in the Georges River initially (2010), then in the Hawkesbury River in 2012 and Tasmania in 2016. Very rapid decontamination protocols and movement restrictions were likely key is slowing the pathogen's spread. The virus has since been observed in wild oyster populations in South Australia but not in cultured oysters there. As in Europe and New Zealand very intensive efforts to breed for resistance to OsHV-1 microvariants in Pacific oysters have characterised the Australian response, and as elsewhere with good success, though the disease remains active. The absence of the OsHV-1 microvariants in cultured oysters in South Australia may reflect the rapid adoption of resistant oyster lines there.

In addition to selective breeding, continuing to limit transfers of infected stocks to protect unaffected areas, strategic placement of farms, and application of farm-level control methods are keys to living with OsHV-1 microvariants. Kirkland noted that there is a strong association of the virus with particulate matter, the sedimenting out of which in the hatchery context is an effective means to locally reduce viral transmission where it occurs. Land-based culture of young spat and window farming are being applied as additional measures for pathogen avoidance. Species diversification, including expanded culture of native Sydney rock oysters and flat oysters *Ostrea angasi*, would contribute to industry resilience.

As a note on selective breeding for disease resistance, Kirkland emphasised that breeding requires a window of at least five years. There is merit to embarking on this proactively, to building a “genetic firewall” in anticipation of an eventual OsHV-1 microvariant emergence. Such was the approach in South Australia, and this has been advocated in the US as well. Outside of preventing pathogen introduction, this may be the best way to ensure resilience of Pacific oyster culture specifically. Waiting to breed for resistance in response to an outbreak that has already happened means that small producers without the diversification in their business profile or financial wherewithal to withstand a half-decade interruption in income will succumb. One question this raises is whether government or other agencies may preferentially “protect” these smaller, most susceptible businesses.

3 Preparing for emerging mollusc pathogens: identification of priorities

Following initial discussions around the presentations by Arzul, Hilton and Kirkland on experiences with OsHV-1 microvariants in Europe, New Zealand and Australia, a break-out session explored the capabilities and communication needed more generally to protect against, detect, and respond to emerging mollusc pathogens. Three groups were charged with addressing the overarching question *Do we have the expertise we need, in the right places with regard to our national and international aquatic animal health management infrastructures, to effectively detect and manage emerging mollusc pathogens (EMOPs)?* through four specific sub-questions:

1) What is this expertise, especially with regard to viral and bacterial pathogens?
2) What essential tools, platforms, and capabilities do we need to have at our disposal?
3) Do we need other tools, platforms and capabilities to understand these pathogens?
4) What questions do we need to be prepared to ask in terms of advancing essential science to inform management?

Wide-ranging discussion in the three break-out groups identified an array of elements, from critical expertise and capabilities to areas of research needing focus and investment, with communication and "framework" elements being most numerous. We distilled these down to thirty-six more or less distinct *needs* or priorities, and each participant was then asked to select the six that she or he viewed as most important, which allowed for a collective ranking of priorities on the list. These priorities (presented in full in Annex 2) may be organized as representing four broad categories, as described in the sections below.

Improving communication and frameworks (18 identified priorities, including seven of the eight highest): The group recognized that improving communication within and across all levels is the highest priority. This includes the effective networking of diagnostic and research laboratories, producers, and regulators and health managers, including education and training of intermediaries in this network. Key intermediaries include professionals such as extension agents, whose familiarity with commercial practices makes them essential agents of communication between farms and laboratories and competent authorities. Coordination among laboratories could be improved, with more sharing of reference materials, protocols, and information of all types; engagement and coordination of competent authorities across all levels could like wise be improved. Better integration and coordination and communication could streamline and strengthen responses to disease events.

The European Community reference laboratory network is a good model for the networking of laboratories. The network led by Isabelle Arzul for mollusc diseases functions very effectively in collating data from across European nations, proficiency testing, and sharing of other relevant information, and a global network of mollusc health experts that functions along the same lines with the existing European structure as its nucleus would have great value for international mollusc health management.

Data sharing is recognized as a major limitation. Improved centralisation and timeliness of data collection and storage would provide clearer perspective on disease status and trends, and allow for more rapid recognition of and responses to emerging concerns. Making this publicly available would do much to improve communication back to stakeholders, in addition to empowering industry to structure their activities, such as seed transfers, with maintenance of biosecurity as a goal. Along these lines, improvement of reporting is important. Inadequate reporting from the commercial sector to alert laboratories and competent authorities about the observation of disease events has long been recognized as a problem with regard to aquatic animal health management worldwide, as was recently highlighted in several presentations at the OIE Global Conference on Aquatic Animal Health in Santiago, Chile. A fundamental structural issue in many places is the lack of adequate, or of any, compensation for production losses related to disease, including in compensation for depopulation of farms conducted in response to a disease emergence. Providing compensation for disease-related losses would be one way to more strongly incentivise reporting from the commercial sector. The group recognized, however, that industry is not the only sector from which reporting should be improved. The scientific community, including diagnostic laboratories and researchers in various areas of aquatic animal health, should be encouraged to more rapidly communicate important observations emerging from their work, particularly in advance of publication in scientific journals. It is often the case that labs will withhold important results pending publication, so as not to be "scooped" and unable to gain maximum publication impact for their work. This can delay notification of important disease perspective by years, and some observations may never eventually be published in journals. A culture change is needed whereby researchers recognise that the most urgent use of some pathogen diversity and epidemiological information is in rapid reporting to promote effective disease management, and where they appreciate further that this reporting does not preclude formal publication of results in the scientific literature. Formally attaching names of investigators to such disease reports, for example in national reporting to the OIE, would ensure that investigators are properly credited for their observations.

The establishment of sensible policies for disease management, with alignment at different levels of government and across regions, is important for the trust it will promote between industry and regulation and the buy-in from industry it will create. Coordinating objectives and harmonising criteria for release from biosecurity restrictions were identified as two priorities under this theme. Increased trust and buy-in are fundamental to strengthening reporting from the commercial sector. Buy-in would also be increased through calibration of pathogen detection and control with focused application to the most impactful points, with regard to disease risk management, in the production process and aquaculture economy. This should be based on robust risk assessments. There should be dialogue as to which pathogens deserve priority for surveillance and control, particularly given that resources are limiting. (Piggy-backing on terrestrial resources such as laboratory infrastructure and diagnostic or epidemiological expertise, where possible, may have merit because of this resource limitation in the marine and aquatic realm.) And regulatory frameworks in general should be flexible with regard to emerging pathogens in particular, given the often urgent need to act with incomplete information. The inadequate response to the OsHV-1 microvar emergence in Europe, which was constrained by questions of how well the pathogen conformed to criteria for OIE listing and which led the pathogen to rapidly spread through most Pacific oyster growing areas and wild populations, highlights the need for this flexibility.

Essential infrastructure and expertise (5 priorities): Standard fields such as pathology, bacteriology, and virology remain foundational to disease diagnostics and aquaculture health management of molluscs and other species, which is critical to the sustainability of mollusc aquaculture industries. There should be a committed focus to broaden expertise in these areas, which has eroded with the retirement of senior scientists in these fields. Basic expertise in these traditional areas allows clear connections to be made between detection (pathogen presence) and the pathology and pathobiology of host-pathogen systems, and opens myriad avenues for their experimental deconstruction. It provides perspective on phenotypic expression in hosts and pathogens that is essential to understanding evolutionary dynamics of such systems, including evolution of virulence in pathogens and resistance and tolerance in hosts. Expanding expertise in these areas will require continued investment in facilities in regional and national laboratories and academic institutions, and a broad focus on education and training in mollusc health.

Strengthening and expanding a focus on traditional diagnostics would, to be sure, represent something of a swim against contemporary tides, in which molecular approaches have become increasingly prominent. While molecular diagnostics and the application of next-generation DNA sequencing technologies, along with proteomic, metabolomic and other approaches, represent powerful tools, they all have their limitations, and should be applied with a clear view of the purposes and environmental contexts to which they are best suited, with robust validation to substantiate this perspective.

The importance of laboratory capacity relates not only to technologies available but to their distribution: the number and geographic location of laboratories. While it is important to have well resourced national and, in the case of the European Union, pan-national laboratories, there is value in maintaining a constellation of regional governmental and academic laboratories, which can be closer and more intimately engaged with aquaculture production in local areas, and familiar with local ecological and oceanographic systems. This is particularly important for large countries such as those of North America, or where language barriers exist as in Europe. The networking of these laboratories and institutions, as noted above, is important, to avoid isolation (including with regard to data reporting) and ensure high levels of proficiency in the application of diagnostics. The OIE Reference Laboratories have a clear role to play here for listed pathogens.

Two other areas of infrastructure and expertise were identified as important for understanding and managing emerging diseases. First, disease challenge models and facilities are essential to testing hypotheses concerning the pathobiology and ecology of disease systems, including those emerging from genetic analyses and surveillance. Environmental DNA (eDNA) analyses applied to production systems may reveal the presence of multiple potential pathogens; the contribution of certain environmental factors may be critical to produce disease and mortality. Experimental systems are essential for providing resolution of such complex scenarios, and in general for building the firm scientific foundations upon which health and disease management must be based. Second, the group acknowledged a sharp limitation of epidemiological expertise, which must be bolstered for effective understanding of, and response to, emerging and established diseases. While here as elsewhere piggy-backing on terrestrial resources may be helpful to some extent – the mathematical underpinnings of epidemiology being transportable from terrestrial to aquatic systems – training and employment of epidemiologists rooted (or immersed) in aquatic systems should be encouraged to ensure adequate expertise in, and support, for health management in aquatic systems.

Key research priorities (10 priorities): Long-term studies can be immensely valuable, and their establishment in key areas should be a top research priority. Long-term perspective is critical for clearly understanding what is normal or "typical" with regard to infection patterns; for appreciating the trajectories of host-pathogen systems, including evolutionary dynamics such as resistance and tolerance evolution versus virulence evolution that would be relevant for management approaches; and for understanding the gradual effects of changing marine and aquatic systems. Incorporating ecological perspective to understand the impacts of these changing environments is essential, and integrating long-term aquatic animal health studies with long-term environmental monitoring, especially where it can be highly resolved through continuous automated monitoring of temperature, salinity, dissolved oxygen, pH, chlorophyll, and so on, would be particularly powerful. While this may not be practical everywhere, establishment of such study systems in key production areas may be prioritised.

With regard to all potentially emerging pathogens but particularly for bacteria and viruses that arguably represent the greatest threat, we must develop strategies for continuously monitoring and characterising the diversity of potential pathogens, including the new variants of known pathogens. For *P. marinus* infecting eastern oysters in the USA, for example, as well as for OsHV-1 microvar and *V. aestuarianus* affecting Pacific oysters in Europe, increases in disease have been associated with the emergence of new phenotypes or genetic variants of established pathogens. Distinguishing among closely related bacterial and viral species and strains, however, and identifying virulence factors underlying pathogenicity of certain strains requires the expertise to identify relevant markers. Maintaining expertise and capabilities for such work should be another priority.

Expanding the capability to pursue metabarcoding and metagenomics to characterise the diversity of potential pathogens, including emerging pathogens in the event of a disease outbreak, would have great merit. But the capability to identify actual pathogens and establish transmissibility must be present as well, so experimental systems to conduct such work are important as noted above. For viral work, this activity would be greatly empowered by the availability of molluscan cell lines, establishment of which unfortunately has remained elusive. An investment in the research to develop such cell lines, for the great value they would potentially have in work with emerging viral pathogens, would be most worthwhile.

The central role of husbandry (2 priorities): Aquatic animal husbandry in the broadest sense, from breeding to maintenance of cultured animal populations and the entire production cycle, offers myriad opportunities to control pathogens and maintain a high level of biosecurity. Understanding disease intersections with aquaculture production for different host-pathogen systems clearly requires an investment in research funding. Focused investment is also required, however, to pursue strategies for aquaculture health management that will emerge from this research. Selective breeding for disease resistance and ploidy manipulation that is already widely practiced in oyster industries are obviously among these strategies. Other approaches, such as training for immunocompetence, may have promise as well. We should seek to build tighter links between the pathology community on one hand, and the breeding and practical aquaculture science communities on the other, to better identify and develop husbandry-based strategies for disease control.

The problem of funding: The nature of funding to detect and manage emerging as well as established shellfish pathogens was a topic that arose often during discussions. Clearly, increased investment in a number of areas outlined above would be beneficial toward these ends. Deserving special mention, however, is the nature of funding available to the pathology and research community to conduct surveillance and research in various areas toward promoting aquaculture health. First, there is not always a good fit between donors and funding agencies and priorities from the perspective of industry and health management. Competition for research grants, for example, will typically be decided based on intellectual merit and scientific innovation. Proposing basic surveillance, despite its immense value in providing perspective on known and potentially emerging pathogens, would not necessarily be competitive in this light. There is a substantial amount of practical aquaculture health-related science, in fact, that would be outside the realm of what reasonably might be supported through competitive grant funding in North America, Europe and elsewhere. Identifying other mechanisms besides competitive grants to support activities like targeted surveillance is essential if we are to close the gaps that exist in our understanding of pathogen distributions (not to mention biology, ecology and other areas) and to maintain adequate vigilance with regard to emerging pathogens. Second, and related to this, the timelines for funding are often inappropriate. Certainly surveillance perspective with regard to established or emerging pathogens would benefit more from sustained funding to support ongoing surveys than from occasional support for "snapshots" into the disease status of shellfish populations. But it is also the case that much of what we need to construct as far as the scientific foundations for managing aquatic animal health would benefit from sustained funding to construct more comprehensive pictures of what is going on. Understanding ecological and evolutionary trajectories of host-pathogen systems in changing marine environments, for example, is not easily accomplished with a single one- or two-year grant. Nor, it should be mentioned, is selective breeding for disease resistance in aquacultured shellfish populations. Yet in both North America and Europe there has been a continuing shift toward shorter funding periods, in part because of political pressure on funding agencies to be able to document rapid impacts and benefits through the funding they provide. There are some longer-term, 4-5 year funding opportunities in Europe, however, that present possibilities for extension to second and third terms; and in New Zealand, some programmes fund 5-7 year projects, and non-contestable core funding for "nationally significant" activities can also be acquired. All of this is constructive, as incorporating at least some capacity for longer-term projects into funding portfolios at the agency level may be beneficial to many areas related to aquaculture health management.

Controlling pathogens and managing the health of aquacultured organisms to support aquaculture growth, finally, is a problem that is global in scale. Critical challenges are common to, and frequently shared across, wide geographic areas. This demands research and engagement by the scientific community that is equally global, which requires the capacity to build and support broad international collaborations. At present, however, while there are some EU and other bilateral funding opportunities, there is no mechanism for developing truly trans-national, collaborative research in this important area. It would be immensely beneficial for sustainable aquaculture development if trans-national research initiatives in aquatic animal health and other aquaculture related fields could be established to support innovation in this area in the future.

4 Relevance to North American interests

The WKEMOP discussions and findings presented above highlight numerous areas deserving attention with regard to emerging mollusc disease preparedness, with respect to OsHV-1 microvariants as well as other pathogens. Improving communication and connectivity among pathology laboratories, regulators, and competent authorities across the US states and Canadian provinces and among the US, Canada and Mexico would have great value, including in information sharing and promoting competence with regard to diagnostics. Weaving an American network of pathologists and aquatic animal health professionals into the EU and broader VIVALDI network, given the deep expertise and resources in Europe that may guide work elsewhere, is critical.

Building deeper relationships between the shellfish health community in North America and commercial interests should continue to be a goal, not least because of the positive contribution these relationships will have on discovery and reporting of emerging disease events (i.e., passive surveillance) and on management of diseases once established. Targeted surveillance in many regions is scarcely adequate; in many US coastal states, there is none. There should be focused dialogue among the pathologists and researchers, regulators and competent authorities, and industry concerning priority species and regions vis-à-vis present and anticipated shellfish aquaculture industry development, and engagement with funding agencies and state/provincial and federal levels to work toward strategies for financial support of this key activity.

It is worrisome that, against a backdrop of great interest in aquaculture development, laboratory capacity and pathology expertise to support this development continues to erode. There should be continued focus on maintaining pathology expertise and facilities in the array of fields necessary to address disease challenges and questions, including shellfish pathology but also bacteriology and virology in addition to contemporary omic (genomics, proteomics, metabolomics) and other methods.

In the US, there has been a move in recent years for some funding to be available for very large grants (> $1M USD), for example through NOAA, to address significant challenges and problems in aquaculture through collaborations of large teams incorporating broad expertise. This development should be applauded: many of the complex problems in aquatic animal health and other areas of aquaculture science can only effectively be addressed with substantial funding extending over several years. Development of sustainable shellfish aquaculture in the Americas and elsewhere would strongly benefit from more such support. Shellfish breeding, about which more will be said below, is an area that essentially demands significant multi-year funding.

With regard to OsHV-1 microvariants in particular, proactivity in breeding for resistance in Pacific oysters grown in North America should be a priority. But how would this best be accomplished? At what scale, and by whom: for example, by private, or public institutions? Not all producers can afford extensive in-house breeding programmes, particularly those proactive against a pathogen not yet established in a geographical area of concern. Presenting a selective challenge of oyster stocks with an exotic pathogen presents additional challenges. Yet industry will be most broadly resilient if the use of disease resistant oyster lines, i.e. the genetic firewall, is widespread. There should be more dialogue among North American producers, regulators, and geneticists and pathologists toward advancing the proactive resistance of Pacific oyster stocks cultured on the continent. This response to the OsHV-1 microvariant challenge can represent a model for future responses to emerging pathogens in the Pacific oyster and other mollusc systems.

Preventing introduction of OsHV-1 microvariants from endemic areas should also be a priority, as should preventing introduction of exotic pathogens, and translocating established pathogens, more generally. Availability of hatchery produced seed remains a limitation, however. The states and provinces of North American countries should consider what they might do to promote establishment of more widely distributed shellfish hatcheries producing locally well adapted seed, to promote vertical integration of industry at more local scales and reduce the necessity of long-distance seed transfers.

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Annex 1: List of participants

Name	Institute	Country of Institute
Isabelle Arzul	Ifremer	France
Colleen Burge	University of Marlyand, Baltimore County	United States
Ryan Carnegie (Co-Chair)	Virginia Institute of Marine Science	United States
Deborah Cheslett	Marine Institute	Ireland
Lori Gustafson	USDA APHIS VS National Veterinary Services Laboratories	United States
Zoë Hilton	Cawthron Institute	New Zealand
Stian Johnsen	World Organisation for Animal Health	France
Peter Kirkland	Elizabeth Macarthur Agricultural Institue	Australia
Árni Kristmundsson	Institute for Experimental Pathology	Iceland
Lone Madsen	DTU Veterinary Technical Univeristy of Denmark	Denmark
Stein Mortensen	Institute of Marine Research	Norway
Gillian Mylrea	World Organisation for Animal Health	France
Ana Roque	Institute for Research and Technology in Food and Agriculture	Spain
Janet Warg	USDA APHIS VS National Veterinary Services Laboratories	United States
Matthias Wegner	Alfred-Wegener-Institute Foundation for Polar and Marine Research	Germany
Janet Whaley (Co-Chair)	NOAA National Marine Fisheries Service	United States

Annex 2: List of identified priorities

Improving communication and frameworks	Responses:
Communication across labs, producers, regulators, etc. (liaisons): educating/training intermediaries (coordinating expertise)	9
Motivate early reporting (e.g., compensation only starts with notification)	7
Sensible policies (alignment at different levels of government/regions)	7
Coordination between diagnostic labs (sharing materials and information), e.g., twinning	6
Encourage reporting first (prior to publication, include a reference)	6
Risk-based pathways - control points identified	5
Public database on disease distribution (curated and easy to enter, not just listed diseases) - improve communication back to stakeholders	5
Flexible regulatory frameworks (for emerging pathogens)	4
Competent authority engagement and coordination across levels, including timely responses	3
Improve centralization (and timeliness) of data collection and storage	3
Piggy-backing on terrestrial resources	2
Harmonize criteria to release restrictions	2
Buy-in; cost-benefit, focus on highest impact pathways	2
Trust and buy-in	2
Coordinating objectives	2
Connect experts to streamline help	1
Target surveillance to risk	1
Prioritization of effort - which pathogens	0

Essential infrastructure and expertise	
Broaden and improve diagnostics - histopathology, electron microscopy, molecular…	3
Preparing professionals - training in methods, field applications, as intermediaries between industry and competent authorities	2
Epidemiology expertise	1
Disease challenge models/facilities	1
Lab capacity - number and distribution of labs	1

Key research priorities	
Long term studies	3
Ecological perspectives	2

Gaps for bacteria/viruses (virulence factor identification, need more bacterial pathogen identification capability)	2
Unknown pathogens: assess whether it is transmissible (which labs do this, how to connect)	2
Continuous monitoring of diversity (marker development, characterize new variants)	1
Improve information about what's normal	1
Cell lines for virology	1
Evolutionary perspectives	0
Expand collection of meta-data (e.g., automated environmental monitoring)	0
Expand metagenomics capabilities	0
The central role of husbandry	
Husbandry/biosecurity to improve health (e.g., source stock from farm versus wild)	6
Selective breeding, ploidy manipulation, trained immunocompetence	1
The problem of funding	
Donors/funds needs better match with industry/health management priorities - including timelines, etc.	1

Note concerning methods: The overall list of priorities presented here was generated in the break-out sessions. Attendees were subsequently asked to each identify their top ~ 6 priorities on an unsorted version of this overall list, which allowed for rankings of all priorities to be generated: the numbers of responses presented in the right column above represent the number of times each listed priority was identified as a top-6 priority by attendees. (Categorisation (4 categories + "the problem of funding") and sorting was post-hoc, for synthesis in this report.) Thus, most identified priorities (18 of the total 36) were associated with "improving communication and frameworks", and these tended to be identified most frequently as "top-6" priorities by attendees; for example, "Communication across labs, producers, regulators, etc." was identified by 9 of 16 attendees as a top-6 priority.