Integrative and Comparative Biology

Integrative and Comparative Biology, volume 56, number 4, pp. 573–587
doi:10.1093/icb/icw048

Society for Integrative and Comparative Biology

SYMPOSIUM

The Use of Filter-feeders to Manage Disease in a Changing World

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From the symposium "Parasites and Pests in Motion: Biology, Biodiversity, and Climate Change" presented at the annual meeting of the Society for Integrative and Comparative Biology, January 4, 2016 at Portland, Oregon.

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Synopsis Rapid environmental change is linked to increases in aquatic disease heightening the need to develop strategies to manage disease. Filter-feeding species are effective biofilters and can naturally mitigate disease risk to humans and wildlife. We review the role of filter-feeders, with an emphasis on bivalves, in altering disease outcomes via augmentation and reduction. Filtration can reduce transmission by removing pathogens from the water column via degradation and release of pathogens in pseudofeces. In other cases, filtration can increase pathogen transmission and disease risk. The effect of filtration on pathogen transmission depends on the selectivity of the filter-feeder, the degree of infectivity by the pathogen, the mechanism(s) of pathogen transmission and the ability of the pathogen to resist degradation. For example, some bacteria and viruses can resist degradation and accumulate within a filter-feeder leading to disease transmission to humans and other wildlife upon ingestion. Since bivalves can concentrate microorganisms, they are also useful as sentinels for the presence of pathogenic microorganisms. While somewhat less studied, other invertebrates, including ascidians and sponges may also provide ecosystem services by altering pathogen transmission. In all scenarios, climate change may affect the potential for filter-feeders to mitigate disease risk. We conclude that an assessment including empirical data and modeling of system-wide impacts should be conducted before selection of filter-feeders to mitigate disease. Such studies should consider physiology of the host and microbe and risk factors for negative impacts including augmentation of other pathogens.

Introduction

Aquatic disease outbreaks can decimate populations, alter community structure, and deplete fisheries, resulting in large economic losses and impacts on fishing communities (Lafferty et al. 2015; Groner et al. 2016). Aquatic environments pose a management challenge as pathogen transmission typically occurs in a 3D water column with complex patterns of water movement, frequently changing water chemistry and temperature, and numerous ecological interactions. In addition to the natural variation in the aquatic environment, climate change impacts both pathogens and their hosts, especially ectothermic species such as invertebrates and fish (Burge et al. 2014). Strategies to manage aquatic diseases and mitigate their impacts are needed and must be able to reduce pathogen loads and or transmission in large bodies of water in a variety of conditions.

One recent management strategy to alleviate infectious disease capitalizes on naturally occurring filtration services of species, such as bivalves, to alleviate pathogen pressure (Maeda 2004; Defoirdt et al. 2011). Bivalves (Phylum Mollusca) such as mussels, clams, and oysters feed by capturing particles from the water using their gills, where particles are selected by size and density (reviewed by Gosling 2003). Selected particles are ingested and released as feces and rejected particles are expelled as pseudofeces (Beninger et al.

Advanced Access publication July 1, 2016

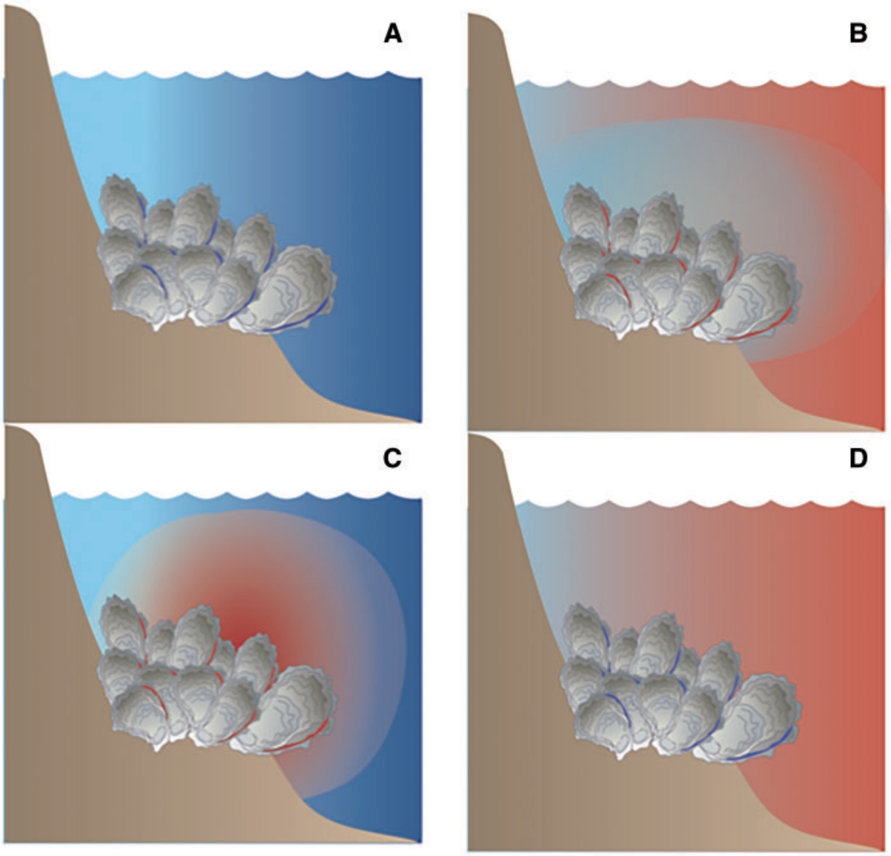


Fig. 1 Four scenarios for filtration within the aquatic environment. (**A**) Neutral—low number of pathogens in both the water column and filter-feeder. (**B**) Subtractive—filter-feeders are reducing the number of pathogens in the water column. (**C**) Additive—the filter-feeders are a reservoir for pathogen replication and emitting the pathogens into the environment. (**D**) No Impact—the filter-feeder does not reduce the pathogen in the water column.

1999; Alexander et al. 2008). Bivalves primarily consume planktonic species, particularly phytoplankton such as diatoms and dinoflagellates (Shumway et al. 1987). Bivalves also consume smaller plankton including bacteria, viruses, and micro-zooplankton, including pathogens, as well as dissolved and particulate organic material (which may contain a rich assortment of microorganisms) (Gosling 2003). As a result, filter-feeding species have the potential to concentrate or remove pathogens.

Individual sessile filter-feeding organisms such as bivalves can clear particles from tens to hundreds of liters of water daily. Filter-feeding species often occur in high population densities, which, when combined with their high filtration capacity, gives these organisms the potential to alter epidemiologic outcomes of pathogens (Ben-Horin et al. 2015). Specific filtration outcomes (Fig. 1) may vary and include little or no discernable impact (either at low or high pathogen concentration), reduction (subtractive) of pathogens through either active or passive filtration, or augmentation (additive) of pathogens when the host acts as a reservoir for pathogens either as a passive or active reservoir (Box 1).

Although the use of filter-feeding species for pathogen control is an attractive management option, little is known about specific applications of biofiltration on pathogen abundance and disease. Currently, the majority of literature is focused on bivalves as biofilters. There is no guide to instruct when and under what conditions bivalves or other filter-feeders may be useful for pathogen mitigation. Given the potential pathogen removal capacity of filter-feeders, we were interested in the following question:

How and when can filter-feeders be used to manage disease?

In order to answer this question, we considered the following:

(1) What are known impacts of bivalve filtration on marine disease?

Box 1 Definitions

Accidental or non-target host: A type of *abnormal host* in which the parasite is not commonly found, yet is suitable for the parasite's development. In some instances (e.g., cysticercosis), the accidental host becomes a "dead end" because even though the parasite develops through its stages, it is unable to be transmitted to the next host and, thus, cannot complete its life cycle.

Active removal: Removal of particles that are targeted and/or selected based on specific parameter (e.g., weight, size, or type).

Clearance rate: Volume of water cleared of suspended particles per unit of time.

Disease mitigation: the act of reducing the impacts of disease (e.g., severity or mortality) in a population.

Filtration rate: Flow rate of water moving across the gills (e.g., pumping rate = volume flow rate).

Infectious disease: A disease caused by a transmissible agent (e.g., a virus, bacterium, protist, macroparasite, fungus, alga, or prion) that infects the host tissues, leading to an identifiable illness or syndrome.

Parasite: An organism (often microscopic) that is metabolically dependent on its host and typically gains energy or food from its host, and may or may not cause disease.

Passive removal: Removal of particles as a side effect of filtering water and/or consuming other particles.

Pathogen: A causative agent (i.e., virus, bacterium, fungus, protist, etc.) of disease; under certain conditions, metazoan parasites (i.e., helminthes and crustaceans) may also cause disease.

Pathogen source: The species or population from which a pathogen is transmitted to other hosts.

Pathogen sink: A host that may become infected with a pathogen but does not transmit the pathogen to other hosts.

Reservoir host: Hosts (environments or populations) that become infected by a pathogen and maintain infections (with or without disease) and serve to transmit the pathogen to susceptible hosts; often in reference to a defined target population (*sensu* Haydon et al. 2002).

Sentinel or indicator: A species with known susceptibility to a specific pathogen or toxin that is sampled over time to assess the presence or absence of the target pathogen or toxin.

Spill-over: Transmission of a pathogen (spills-over) from a reservoir or maintenance host, often domesticated, to sympatric wild host species. The reservoir species may be non-native or introduced to a new locale and introduce the pathogen into a native population.

Spill-back: "Reverse spill-over" occurs when pathogen transmission occurs from a native host that acts as reservoir for transmission back to maintenance species that introduced the infectious agent. Spill-back may occur when wild, native species transmits the pathogen to back to domesticated animals (*sensu* Daszak et al. 2000).

(2) Which other high-filtration capacity invertebrates may function as pathogen biofilters?
(3) What makes a pathogen more resilient to filtration or degradation?
(4) What are the potential impacts of ocean or climate change on interactions between filter-feeders and pathogens?
(5) What are management implications of filter-feeders?
(6) How can modeling inform management approaches?

Finally, we provide conclusions and future directions for the use of filter-feeders for disease management.

What are known impacts of bivalve filtration on marine disease?

Bivalves often exist in dense beds providing necessary structure and habitat for a variety of species, and improving water quality by directly filtering pathogens and suspended matter from the water column (Ward and Shumway 2004; Coen et al. 2007). In Fig. 2, we focus on epidemiological outcomes of pathogen filtration in bivalves. In this scenario, pathogens may be amplified through aggregation and replication within reservoir hosts or reduced through direct ingestion. Live pathogens may be released into the environment attached to feces or pseudofeces. We will focus the following

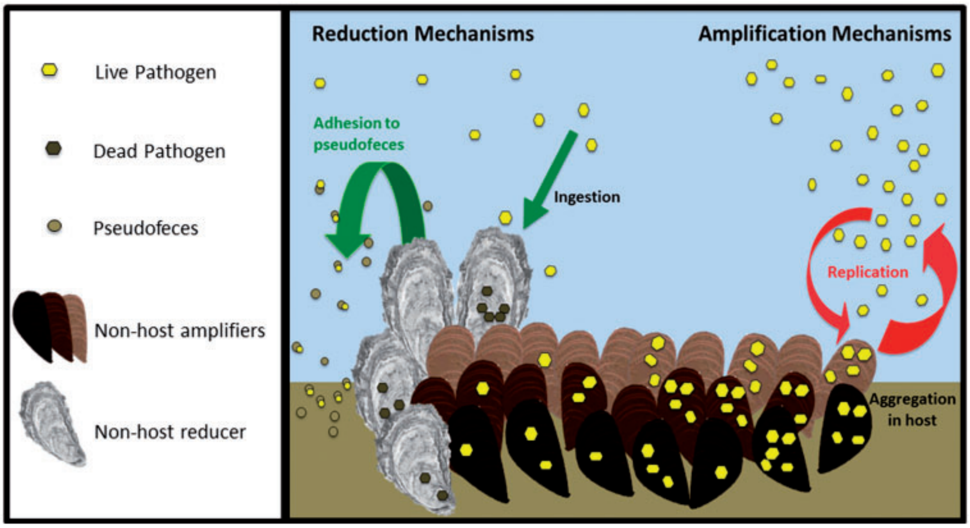


Fig. 2 Filter-feeders can alter pathogen transmission through reduction or amplification. Reduction can occur via mechanisms such as ingestion by non-target filter-feeders (dark arrow) or incorporation into pseudofeces made by the filter-feeder that sink out of the water column (curved arrow). Amplification occurs when the pathogen successfully replicates inside or on the filter-feeder (arrows) or if aggregation in the filter-feeder increases the likelihood of transmission.

section on transmission augmentation (amplification) and transmission reduction.

Transmission augmentation

The role of bivalves in the transmission of human pathogens is well documented and their role in transmission of wildlife disease is gaining attention. Bivalves can filter and concentrate human pathogens and serve as a passive reservoir for viruses [e.g., Hepatitis A or Norovirus (Enriquez et al. 1992; Schwab et al. 1998), bacteria (e.g., *Vibrio* spp. and *Escherichia coli*, Ismail et al. 2015)], diatoms and dinoflagellates (e.g., toxin producing *Pseudo-nitzchia* spp., Amzil et al. 2001, *Alexandrium*, and *Gymnodinium* spp., Bricejli and Shumway 1998), and protists (e.g., *Cryptosporidium*, Gómez-Couso et al. 2006). In addition, bivalves can act as a passive reservoir for pathogens of wildlife. For example, mussels (*Mytilus galloprovincialis*), are known intermediate hosts for *Toxoplasmosis gondii*, which commonly infects sea otters (Arkush et al. 2003). Oysters in the genus *Crassostrea* (*C. gigas*, the Pacific oyster, and *C. virginica*, the eastern oyster) have been shown to act as passive reservoirs for pathogenic fish reoviruses (Meyers 1980, 1984). A second type of augmentation occurs when a bivalve is an active reservoir, and pathogen replication occurs within the host leading to transmission within or between species (see Ben-Horin et al. 2015 for an in-depth review of pathogen transmission in bivalves).

Transmission reduction

Consumption and degradation of parasites (referred to as degradation in this review) is an effective means to reduce pathogen loads in aquatic environments (Table 1). Filter-feeders that may mitigate disease by pathogen removal, such as mussels and oysters, can specifically select particles based on size (Gosling 2003). Therefore, it is presumed that they "actively" remove larger or specific organisms for consumption. For example, in the presence of the non-host Pacific oyster, metacercariae stages of the parasite *Himasthla elongata* in *Cerastoderma edule* (cockles) were reduced by up to 91% (Thieltges et al. 2008; Welsh et al. 2014). Despite generally selecting for particles of 4–250 μm (Gosling 2003) some species of bivalves, as well as other filter-feeders (e.g., sponges and sabellid worms), are capable of removing microbial pathogens including viruses (Hadas and Marie 2006; Faust et al. 2009; Granada et al. 2014). For example, the Asiatic clam (*Corbicula fluminea*) can successfully remove and avian influenza virus from the water column, reducing infection rates in wood ducks *(Aix sponsa)* (Faust et al. 2009).

Pathogens can be removed from the water column by means other than selective filtration. For example, Pacific oyster shells reduced free-living *H. elongate* trematode parasites by 44% despite containing no filter-feeding organism, suggesting that adhesion to the shell may play a role in parasite reduction (Welsh et al. 2014). Bacteria and viruses have also been shown to attach to clay particles, such as those

Table 1 Examples of freshwater and marine filter-feeders that have caused pathogen reduction from the water column or within a host species

Habitat	Filter Feeder Taxon	Species	Pathogen Taxon	Species/particle	Citation
Freshwater	Bivalve	*Corbicula fluminea*	Virus	*A/Mallard/MN/190/99 (H3N8)*	Faust et. al. 2009
		Sphaerium sp.	Trematoda	*Ribeiroia ondatrae*	Orlofske et al. 2012^{ns}
		Dreissena polymorpha	Conoidasida	*Cryptosporidium parvum*	Graczyk et al. 2003
Marine	Bivalve	*Crassostrea gigas*	Trematoda	*Himasthla elongata*	Welsh et. al. 2014, Thieltges et al. 2008b, 2009
		Mya arenaria	Trematoda	*H. elongata*	Thieltges et. al. 2008b
		Marcoma balthica	Trematoda	*H. elongata*	Thieltges et al. 2008b^{ns}
		Mytilus edulis	Trematoda	*H. elongata*	Thieltges et al. 2008b
	Crustacean	*Semibalanus balanoides*	Trematoda	*H. elongata*	Welsh et al. 2014
		Austrominius modestus	Trematoda	*Echinostephilla patellae*	Prinz et al. 2009
	Gastropod	*Littorina littorea*	Trematoda	*Parorchis acanthus*	Prinz et al. 2009
		Patella vulgata	Trematoda	*P. acanthus*	Prinz et al. 2009
		Crepidula fornicata	Trematoda	*H. elongata*	Thieltges et al. 2008b
	Porifera	*Hymeniacidon perleve*	Bacteria	*Escherichia coli*	Fu et al. 2006
		Chondrilla nucula	Bacteria	*E. coli*	Milanese et al. 2003
		H. perleve	Bacteria	*Vibrio anguillarum II*	Fu et al. 2006
		Negombata magnifica	Virus	Unknown	Hadas and Marie 2006
	Polychaeta	*Branchiomma luctuosum*	Bacteria	*V. alginolyticus*	Licciano et al. 2005
		Sabella spallanzanii	Bacteria	*V. alginolyticus*	Licciano et al. 2005

ns: indicates studies where reduced the pathogen loads were not statistically significant.

found in sediment and pseudofaeces (Syngouna and Chrysikopoulos 2010). Sediment particles, including clay and pseudofaeces, often sink out of the water column, removing the attached bacteria and viruses from areas where transmission is likely (Haven and Morales-Alamo 1972).

Which other high-filtration capacity invertebrates may function as pathogen biofilters?

While their role in changing water quality may be less well-studied, organisms such as sponges and ascidians are important filter-feeding invertebrates and can also act as bio-filters. Here, we review the known effects of these taxa on pathogen transmission.

Sponges

Sponges (Phylum Porifera) have high filtering and clearance rates of microbes and have been used as remediation tools and biofilters for aquaculture in regions around the world (reviewed by Wilson et al. 2012; Ledda et al. 2014). Sponges filter large amounts of seawater; up to 14 l/h/m^2 of tissue (Milanese et al. 2003). As suspension feeders, filtration by sponges is considered non-selective. Nonetheless, this method is effective at removing >25% of the dissolved and particulate total organic carbon (TOC) from the water column, which contributes to sustaining the microbial symbionts that make up more than two thirds of the sponge biomass (Yahel et al. 2003). While it is presumed that pathogen removal is a side effect of filtering pico- and nanoplankton from large volumes of water (Maldonado et al. 2010), selective consumption of specific pathogenic microbes has been measured in controlled laboratory studies with sponges (Maldonado et al. 2010). Pathogens of other organisms, such as the putative causative agent of sea fan aspergillosis, *Aspergillus sydowii*, have been found in sponges with no signs of disease (Ein-Gil et al. 2009; Negandhi et al. 2010). As a result, sponges have been proposed as a bioremediation tool to clear pathogens of wild species from the water column (Milanese et al. 2003; Fu et al. 2006; Stabili et al. 2006; Longo et al. 2010).

Ascidians

Ascidians (Phylum Chordata) are solitary or colonial filter-feeding marine invertebrates and may reduce abundances of potential pathogens in the marine environment. Ascidians pump seawater through their branchial basket and collect particles on a mucus filter that covers the inner wall of the pharynx (Randlov and Riisgård 1979). Although particles that range in size from 0.5 to 100 µm are ingested, those measuring greater than 600 nm have the highest retention rate (e.g., phytoplankton and larger bacteria; Peterson 2007). Filtration rate varies with ascidian size, seawater temperature, and particle concentration (Peterson and Riisgård 1992). Ascidians can filter up to 200 ml/min but many filter in the range of 10–100 ml/min (Randlov and Riisgård 1979). In one study, *Ciona intestinalis*, a solitary ascidian that can form dense aggregations, filtered 5–34 ml/min and was estimated to be able to filter the entire volume of the studied cove in Denmark daily (Peterson and Riisgård 1992). The role of ascidians in biofiltration depends upon the pathogens in the water column. The colonial ascidian, *Polyundrocarpa zorritensis*, ingests bacteria and can reduce seawater concentrations of allochthonous bacteria, including pathogens; however, it can also concentrate bacteria and may serve as a reservoir for some pathogen species due to differential digestion of bacterial taxa (e.g., Gram-negative bacteria, Stabili et al. 2015). Similar to bivalves and sponges, ascidians have potential as biofilters for pathogen remediation, but knowledge gaps about whether the target pathogen is filtered, retained, and or digested need to be addressed (Stabili et al. 2015).

What makes a pathogen more resilient to filtration or degradation?

Pathogens have evolved mechanisms to resist degradation from the tissues of filter-feeders. Outbreaks of bacterial and viral diseases in humans associated with bivalve consumption demonstrate that some microorganisms are able to resist degradation and persist in bivalve tissues. Bacterial genera that survive in the tissues of bivalves and resist degradation include *Salmonella* and *Vibrio* species (Jones et al. 1991; Wright et al. 1996; Hernroth et al. 2002; Pruzzo et al. 2005). These species are responsible for the most cases of bacterial-caused food poisoning associated with bivalve consumption and are readily isolated from bivalves (Jones et al. 1991; Rippey 1994; Wright et al. 1996; Potasman et al. 2002; Hernroth et al. 2002). Viruses that survive in the tissues of bivalves and resist degradation are frequently non-enveloped viruses, such as noroviruses (Potasman et al. 2002). It is unclear whether this morphological trait influences persistence in bivalve tissues. While components of the envelope often facilitate virus entry and evasion of host immunity (Wyatt and Sodroski 1998; Poranen et al. 2002), non-enveloped viruses are generally more persistent in aquatic environments (Sobsey and Meschke 2003).

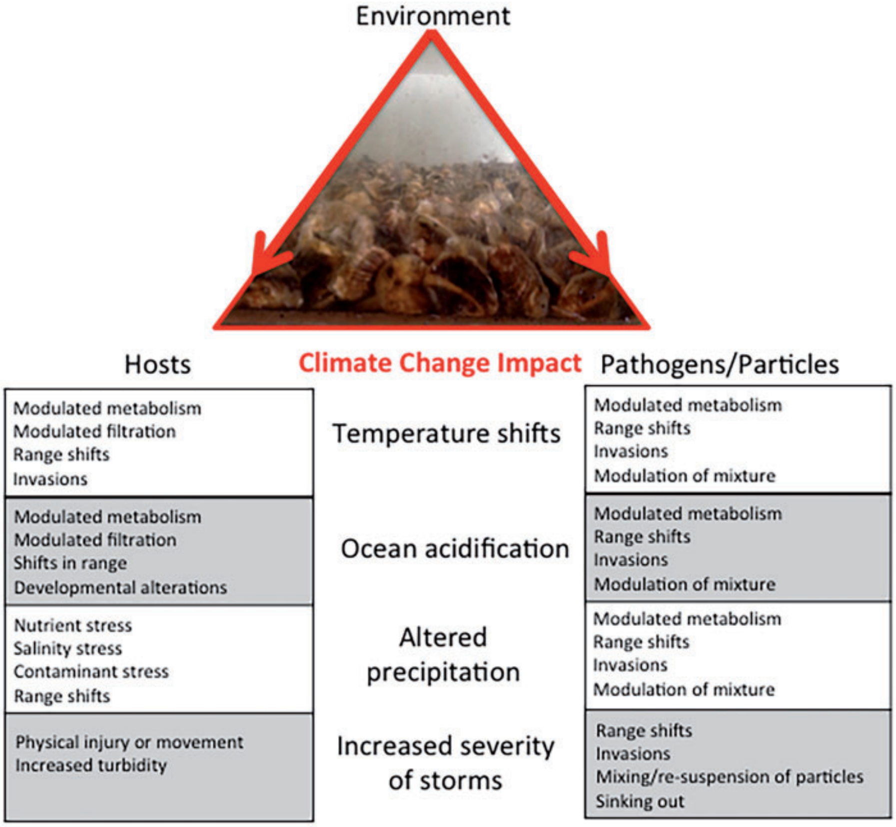
Pathogen characteristics that determine resistance or susceptibility to degradation may include mechanical features such as particle size. Many studies have correlated clearance rate as a function of particle size although this varies somewhat with species (Riisgård 1988, 1998; Sprung and Rose 1988; Lei et al. 2001). For example, *C. gigas* and *M. edulis* can filter eukaryotic diatoms (>4 µm width) with 100% efficiency, but filtration efficiency decreases with decreasing particle size (Haven and Morales-Alamo 1970; Riisgård 1998). Viruses, which are often less than 200 nm in size, are generally more resistant to degradation than bacteria (Polo et al. 2015). Human enteric viruses such as Norovirus and Hepatitis A virus are the most common pathogens transmitted by consumption of bivalves (Lipp and Rose 1997; Potasman et al. 2002; Lees 2000). Filtration efficiency of small microorganisms can increase when microbes are attached to organic aggregates, also called marine snow (Lyons et al. 2005; Kach and Ward 2008; Froelich et al. 2013). In particular, pathogenic *Vibrio* spp. have been shown to accumulate on marine snow (Keyhani and Roseman 1999). Thus, while size affects susceptibility to filtration, this general rule is impacted by particle aggregation.

The bivalve immune system may also influence the resistance of microorganisms to degradation. Persistence of bacteria in bivalve tissues is dependent on their sensitivity to the bactericidal activity of the hemocytes (primary immune cells) and soluble immune factors (Pruzzo et al. 2005). For example, various *Vibrio* species have a higher capacity to survive in mussel hemolymph than do *E. coli* (Prieur et al. 1990; Croci et al. 2002). Specific molecular mechanisms of binding to bivalve tissues can also affect resistance to degradation. For example, Pacific oysters have been shown to differentially concentrate various strains of Norovirus (Le Guyader et al. 2006) via binding to ligands present in different oyster tissues (Maalouf et al. 2010, 2011).

These examples of resistance to bivalve degradation stress the need for more basic research on the interactions between specific microbes and various filter-feeders. This type of research will allow management agencies to match the most effective filter-feeder for a particular environment.

What are the potential impacts of ocean or climate change on interactions between filter-feeders and pathogens?

Current and future climate change conditions in the world's ocean will continue to impact marine species



Hosts	Climate Change Impact	Pathogens/Particles
Modulated metabolism Modulated filtration Range shifts Invasions	Temperature shifts	Modulated metabolism Range shifts Invasions Modulation of mixture
Modulated metabolism Modulated filtration Shifts in range Developmental alterations	Ocean acidification	Modulated metabolism Range shifts Invasions Modulation of mixture
Nutrient stress Salinity stress Contaminant stress Range shifts	Altered precipitation	Modulated metabolism Range shifts Invasions Modulation of mixture
Physical injury or movement Increased turbidity	Increased severity of storms	Range shifts Invasions Mixing/re-suspension of particles Sinking out

Fig. 3 Climate change impacts on pathogen filtration. Shifts in the environment are leading to ocean change, including (1) changes in temperature, (2) ocean acidification (increased $C0_2$, decreased pH), (3) altered precipitation (leading to changes in salinity) and (4) increased severity and or number of storms and cyclones. All of these factors are acting to change the interaction between the host and potential pathogens or particles.

(Doney et al. 2012; Howard et al. 2013; Burge et al. 2014), including disease-causing microbes (Burge et al. 2014) and filter-feeding bivalves (Kroeker et al. 2013). Physical ocean changes (e.g., warming, acidification, circulation, salinity, storms, hypoxia, and additional changes) impact the biology of the organisms inhabiting the ocean, both through physiological changes (linked to temperature, salinity, hypoxia, nutrients, pH, etc.) and population shifts (invasions, biological interactions between species, community composition, and biodiversity), which ultimately can lead to ecosystem changes (Doney et al. 2012; Nagelkerken and Connell 2015). Climate change and its associated processes may, thus, influence how filter-feeders reduce or augment disease (Fig. 3). For example, non-cholera *Vibrio* disease outbreaks in humans (caused by *V. vulnificus* and *V. parahemaolyticus*), increase with warmer temperatures and extreme storm events (reviewed by Burge et al. 2014). Increased temperatures facilitate bacterial growth as well as increase expression of virulence factors, such as hemolysins (Mahoney et al. 2010). Climate change is expected to alter temperatures at which filter-feeders could be exposed to during emersion and air exposure during low tides (Doney et al. 2012). Both bivalves and particles they filter (i.e., "microbial" and "macroparasite" pathogens and phytoplankton food sources) have temperature-dependent metabolic rates (Burge et al. 2014; Moran 2015; Nagelkerken and Connell 2015). Temperature may act to increase consumption rates by herbivores (including bivalves), and shift abundances and production of available members of the ocean plankton and microbiome (Nagelkerken and Connell 2015). However, we are far from understanding the complex trophic structure of the ocean microbiome under warming conditions (Moran 2015; Sunagawa et al. 2015).

For bivalves, elevated water temperature within physiological tolerable ranges typically increases filtration rates. Such increases, in turn, can influence how filter-feeders interact with pathogens. For example, higher filtration rates may clear more pathogens from the water and reduce infection intensity in downstream hosts (Goedknegt et al. 2015). Increases in filtration with increased temperature is

Table 2 Current and proposed uses of filter-feeders to for disease mitigation

Filter-feeder Taxon	Species	Pathogen	Pathogen host	Citation
Bivalve	Atlantic sea scallop(*Placopectin megellanicus*)	Sea lice (copepods)	Atlantic Salmon	Bartsch et al. 2013
	Blue mussels (*Mytilus edulis*)	Sea lice	Atlantic Salmon	Bartsch et al. 2013
	Asiatic clam (*Corbicula fluminea*)	Avian influenza virus	Birds	Faust et al. 2009
	Freshwater mussel (*Anondonta californiensis*)	*E. coli*	Various	Ismail et al. 2015
Porifera	*Hymeniacidon perlevis*	Various bacteria	*Mediterranean mussel (Mytilus galloprovincialis)*	Longo et al. 2010, 2015
Polychaeta	*Sabella spallanzanii*	Various bacteria	Humans	Stabili et al. 2006, 2010
	Ircinia variabilis	Various bacteria	Various	Ledda et al. 2014
	Agelas oroides	Various bacteria	Various	Ledda et al. 2014
Ascidian	*Polyandrocarpa zorritensis*	Various bacteria	*Various*	Stabili et al. 2015

not a linear relationship; filter-feeders eventually reach a maximum temperature threshold, after which the filtration rate declines (Sylvester et al. 2005; Goedknegt et al. 2015). Thus, understanding physiological limits is essential when selecting potential species for use as biofilters.

Other ocean conditions and inputs can also be altered as a result of climate change and may affect how filter-feeders interact with pathogens. In marine systems, ocean acidification due to increased atmospheric partial pressure of carbon dioxide (pCO_2), terrestrial run-off, and other biotic and abiotic inputs will result in marine hypercapnia (increased CO_2; Feely et al. 2012). Ocean acidification can affect the soft tissues of filter-feeding organisms by altering metabolism (Lannig et al. 2010; Liu and He 2012; Waldbusser et al. 2015), decreasing body condition (Lannig et al. 2010), and hindering larval development (Gazeau et al. 2010; Barton et al. 2012). In addition, the reduced pH caused by the increase in CO_2 can affect the calcareous shells of bivalve species by reducing their ability to deposit new layers and the dissolution of existing shell material (Barton et al. 2012). Ocean acidification is also predicted to impact the abundance (e.g., by increasing pelagic density) of some potential pathogen species, while having no impact on other species (Nagelkerken and Connell 2015).

Effects of climate change on aspects of filter-feeder development and physiology is species dependent (Liu and He 2012). Extreme weather conditions are expected to occur more frequently with climate change and filter-feeders may not be able to adapt to these predicted extreme and rapid fluctuations (Kayler et al. 2015). The majority of conclusions regarding the effects of climate change on organismal ecology are based on short-term mesocosm or laboratory experiments, and thus the long-term effects of temperature or ocean acidification and adaptations of the filter-feeders and pathogens remain largely unknown. Recent studies have shown positive carry-over effects of ocean acidification exposure to adult Sydney rock oysters on their progeny and subsequent generation (Parker et al. 2015). Combined with the lack of studies on interactions between filter-feeders and pathogens it is difficult to predict with certainty how the augmentation or mitigation of diseases by filter-feeders will be affected by climate change.

What are management applications and implications of filter-feeders?

Pathogen reduction in aquaculture

Aquaculture is on the rise globally and is an important source of revenue and protein (SOFIA 2014). Losses due to infectious disease have increased over the past decades making disease control a priority in aquaculture development and resource conservation (Krkošek et al. 2007; Groner et al. 2016). Intensive farming often involves the culturing of genetically similar and or high densities of individuals, which can facilitate density-dependent outbreaks of disease (Jansen et al. 2012). At the same time, natural "controls" for disease mitigation may be missing from such systems. Control mechanisms include predation of diseased individuals or their pathogens, evolution of disease resistance in hosts, geographical separation of host life stages, and dilution of pathogens among hosts and non-hosts. Pathogen filtration by bivalves has been proposed as a method for reducing disease risk of farmed and nearby wild organisms (Faust et al. 2009; Bartsch et al. 2013) (Table 2). The viability of this approach depends upon the pathogen in question, the filtration species chosen, and their interactive effect on other pathogens in the system. For example, lab studies demonstrated that blue mussels

Table 3 Current and proposed use of bivalves and other filter-feeders as sentinels for pathogens

Filter-feeders Taxa	Species	Program or Location	Pathogens detected	Citation
Bivalves	Asiatic clams (*Corbicula fluminea*)	Trials	Avian Influenza	Huyvaert et al. 2012
	Mussels (*Mytilus chilensis*)	Chile	Hepatitis A virus	Enriquez et al. 1992
	Mussels (*M. edulis*)	Skagerrak coast Sweden	Adenoviruses, enteroviruses, Norwalk-like virus	Hernroth et al. 2002
	Mussels (*M. californianus*)	California Coast	*Salmonella* spp., *C. perfringens*, *P. shigelloides*, *Vibrio cholerae*, *V. parahaemolyticus*, *V. alginolyticus*	Miller et al. 2006
	Mussels (*M. californianus*)	California Coast	*Cryptosporidium*	Miller et al. 2005
	Mussels and oysters various species	USA (Mussel Watch)	Various	Powell et al. 2015
	Mussels and oysters various species	Spain (Various)	Various	Muniain-Mujika et al. 2003
	Dresseneid mussels (*Corbicula fluminea*, *Dreissena* spp.)	Great Lakes/St. Lawrence River (North America) Shannon River (Ireland)	*Cryptosporidium, Giardia, Cyclospora, Enterocytozoon*	Conn et al. 2013; Ladeiro et al. 2014; Mezzanotte et al. 2016
Polychaeta	*Branchiomma luctuosum*	Mediterranean sea	Various bacteria	Stabili et al. 2006
	Sabella spallanzanii	Mediterranean sea	Various bacteria	Licciano et al. 2007
Porifera	*Hymeniacidon perlevis*	*In trial*	Various bacteria	Longo et al. 2010, 2015
	Spongia officinalis	*In trial*	Various bacteria	Stabili et al. 2008

(*Mytilus edilus*) and Atlantic sea scallops (*Placopectan megellanicus*) can ingest sea lice (*Lepeoptheirus salmonis*), which are a significant pest of wild and farmed salmon (Molloy et al. 2011; Bartsch et al. 2013). However, lab studies showed that these bivalves may concentrate infectious pancreatic necrosis virus (IPNv), an important pathogen of Atlantic salmon, releasing the virus in their feces for up to 7 days post-exposure (Molloy et al. 2013). The success of bivalve filtration will depend upon the relative risk of these two diseases locally.

Use of bio-filtration in aquaculture needs to consider the influence of environmental conditions (see previous section for more details). For example, low temperature and runoff influenced the uptake and accumulation of F+Coliphage during the winter months with a concentration up to 99-fold relative to other seasons (Burkhardt III W and Calci 2000, Hernroth et al. 2002). Intentional manipulation of environmental conditions can be used to facilitate parasite–filter-feeder interactions. Sea lice are attracted to light, thus placement of light near filter-feeders may concentrate sea lice where they can be ingested (Bartsch et al. 2013). This type of application is particularly promising for the development of integrated multi-trophic aquaculture because many filter-feeders have economic value.

Bivalves have also been suggested as a means of reducing pathogen exposure in other molluscs. For example, oysters placed near mussel farms had a lower risk of exposure to Ostreid herpes virus (OsHV-1) than those placed away from mussel farms (Pernet et al. 2014). Interest in using bivalves to filter out pathogens is also being investigated with land-based farms to reduce the microbial loads in farm effluent. For example, oysters, mussels, and other filter-feeding organisms are being evaluated to reduce the potential for release of a bacterial pathogen from an abalone farm (Friedman et al., unplubl. data). Bivalves are not the only organisms being considered for disease management in aquaculture. Two sabellid worm species from the Mediterranean, *Branchiomma luctuosum* Grube and *Sabella spallanzanii* Gmelin, have been proposed as biofilters in aquaculture for their high-filtration rate of bacterioplankton and reduction of the bacterium *V. alginolyticus* (Licciano et al. 2005). New applications of filter-feeders for pathogen management are likely to emerge as aquaculture continues to increase.

Using bivalves as indicator species

Due to their proclivity to concentrate pathogens, there is considerable value in using bivalves as sentinels to monitor disease risk (Table 3). For example, the NOAA mussel watch program monitors bivalves for the presence of human pathogens, toxins, contaminants, and parasites. This program has led to regulatory decisions and follow-up monitoring to evaluate management programs (Kim and Powell 2007). Invasive dresissenid bivalves (*Corbicula fluminea* and *Dresisena* spp) have been used for pathogen monitoring in the Great Lakes system (North America) and in the Shannon River (Ireland), where dresissends are used as sentinels for human and animal pathogens including *Cryptosporidium, Giardia, Cyclospora, Enterocytozoon*, and *Encephalitozoon* (Conn et al. 2013). While highly quantitative comparisons among sites may not be possible using sentinels due to variation in accumulation rates, sampling of bivalves has proven to be an effective method to detect the presence of pathogens, which may be hard to detect in the water column or target hosts.

Impacts of introduced species

The introduction of nonnative and reintroduction of recently extirpated native bivalve species (restoration aquaculture) has been suggested as a viable way to reduce the level of human pathogens in the water column for both saltwater (NAS 2004) and freshwater ecosystems (Ismail et al. 2015). For example, a recent laboratory study indicates the reintroduction of *Anadonta californiensis*, a species of freshwater mussel once found in Mountain Lake, California (once the source of drinking water to the city of San Francisco) may facilitate removal of *E. coli* (Ismail et al. 2015). Other studies have shown that invasive filter-feeders efficiently remove native pathogens from the new location and thus effectively mitigate disease outside of their natural range (Thieltges et al. 2009; Welsh et al. 2014; Goedknegt et al. 2015). For invasive species that thrive in warmer temperatures such relief from pathogens may be welcomed by native hosts, which may already be stressed by increased water temperatures thus making the mitigation effects greater.

Movement of non-native filter-feeders can be risky. *C. gigas*, has been cultured outside of its natural range and has subsequently colonized many coastal regions throughout the world (Troost 2010). Introduction of *C. gigas* from Japan to California, USA is linked to the introduction of *Haplosporidium nelsoni* into Tomales Bay, CA. (Burreson et al 2000). Movement of infected *C. gigas* to the US east coast from the Pacific (either directly from Asia or from California) is believed to be the potential vector for transmission of this pathogen to the native oyster, *C. virginica* (spill-over; Daszak et al. 2000) (Burreson et al. 2000; NAS 2004). Similarly, native pathogens can infect and be amplified by invasive species and resulting in an increased local pathogen population and spill-back into the native species (Daszak et al. 2000, NAS 2004). For example, the Suminoe oyster, *C. ariakensis*, was considered for introduction to the Chesapeake Bay in order to restore lost ecosystem services (including removal of human pathogens) that were previously provided by oysters (NAS 2004). Ultimately, this oyster was not introduced into the Chesapeake Bay, in part, due to concerns about potential introductions and amplification of oyster diseases by this species (NAS 2004). These observations demonstrate the complex trade-offs that occur when moving filter-feeders.

How can modeling inform management approaches?

The impact of pathogen filtration by non-host organisms on disease dynamics depends on numerous processes occurring within and among filter-feeders (Powell and Hofmann 2015). Much of what we know about the role of filter-feeders on pathogen abundance and persistence comes from laboratory studies and it is unclear how the patterns “scale-up” in larger, more complex environments. There is potential for non-linear effects of filtration on pathogen dynamics and complex, environmentally-dependent mediators of these interactions. In cases where pathogen filtration may be considered as a management approach, modeling is advised for identifying the levels of filtration necessary to alter transmission among host organisms, the environmental conditions when filtration is an appropriate strategy, and potential trade-offs associated with the approach (e.g., unintended pathogen augmentation and non-linear effects). Recent modifications of typical Anderson-May type Susceptible-Infected (SI) models to Susceptible-Infected-Particle (SIP) models may prove valuable for calculating the effects of filtration on transmission in aquatic environments (Murray 2009; Bidegain et al. 2016). Such models were specifically designed to examine the epidemiology of disease in aquatic environments, where transmission is typically density-dependent and occurs from the water column. Pathogens (or particles) are modeled as a concentration in the water column, or an absolute number within host or non-hosts, thus specific effects of the filter-feeder on the pathogen can be modeled directly (e.g., degradation, clearance, replication).

Transmission of pathogens from the water column to receptive hosts is dependent on numerous biological, physical, and chemical properties including environmentally dependent growth and survival of the pathogen, tides, currents, temperature, and pH (Powell and Hofmann 2015). Such factors are often heterogeneous over space and time and may not be amenable to SIP models. An alternative approach is to use gridded hydrodynamic models or FVCOM (Finite Volume Ocean Circulation Models), which model the movement of particles over space and time. Although FVCOM models are computationally expensive and are only practical for simulating dynamics of local or regional areas, they may be useful for identifying source-sink dynamics of pathogens (Salama et al. 2013). In theory, these models could inform strategic placement of filter-feeders to have a maximum effect on disease dynamics. Such environmentally-dependent models can be used to investigate future scenarios (e.g., with climate change).

As with many disease models, parameterization and validation are some of the biggest challenges for the proposed models. Such models require estimation of (1) filtration and degradation (or replication) rates, (2) contact rates between pathogens, filter-feeders, and hosts, and (3) impacts of infection on host survival, fitness, and production of pathogens. Validation of model outcomes requires field measurements of disease rates, quantification of density, and filtration rates by accidental (non-target) hosts and often requires multidisciplinary collaboration.

Conclusions and future directions

As the necessity for marine disease management increases, so does the need for strategies to reduce pathogen transmission. Bivalves and other species can provide a potent ecosystem service by efficiently filtering some pathogens. Bivalves are also valuable as pathogen sentinels due to their capability to bio-concentrate pathogenic microorganisms. Many knowledge gaps need to be overcome to evaluate the utility of a specific species to filter target pathogens, as well as the potential for the filter-feeder to act an active reservoir and convey pathogenic microorganisms to humans or wildlife. Careful choice of a robust combination of filter-feeder and pathogen is needed for efficient management (for transmission reduction or pathogen monitoring), particularly when the filter-feeder is introduced. Key knowledge gaps to investigate include calculating the optimal density of the filter-feeder's hosts both in the capacity of filtering and evaluating the potential for increased disease risk to both the filter-feeder and possibility of augmentation (active or passive). It is clear that diseases of the filter-feeder themselves may impact ecosystem services provided. In addition to the filter-feeding host, the natural symbionts (meta-organism or holobiont) may be collectively responsible for the filter-feeders ability to reduce pathogen loads, though research in this field is limited. In the future, screening of host symbionts may be an integral part of choosing particular species or cohort of animals for disease management. In addition, paired studies using empirical data and modeling may be useful for understanding how filter-feeders reduce pathogens, and how ocean change may play a role in the capacity of the biofiltration.

Acknowledgements

We also thank N. Rivlin who provided technical assistance and D. Harvell, R. Carnegie, and E. Schott who provided editorial comments.

Funding

This review was completed as part of the Ecology of Infectious Marine Disease RCN Workshop (OCE #1215977). We thank the Friday Harbor Laboratories and the School of Aquatic and Fishery Sciences, University of Washington, for providing resources.

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