Mechanisms by which predators mediate host-parasite interactions in aquatic systems

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Abstract

It is often assumed that predators reduce disease prevalence and transmission by lowering prey population density and/or by selectively feeding on infected individuals. However, recent studies, many of which come from aquatic systems, suggest numerous alternative mechanisms by which predators can influence disease dynamics in their prey. Here, we review the mechanisms by which predators can mediate host-parasite interactions in aquatic prey. We highlight how life histories of aquatic hosts and parasites influence transmission pathways, and describe how such pathways intersect with predation to shape disease dynamics. We also provide recommendations for future studies; experiments that account for multiple effects of predators on host-parasite interactions, and that examine how predator-host-parasite interactions shift under changing environmental conditions, are particularly needed.

Impacts of predators on aquatic host-parasite interactions

Predators can mediate host-parasite interactions in their prey via a range of direct and indirect mechanisms. It is frequently assumed that predators will reduce disease prevalence and transmission by reducing prey population densities below the required threshold for disease transmission or by selectively feeding on infected individuals (known as the 'healthy herds hypothesis') [1]. In some instances, predators do reduce parasite populations in prey, yet there are also numerous cases where increased parasite prevalence or transmission is observed instead [2]. It is also increasingly clear that predators mediate host-parasite interactions through a wide array of mechanisms alongside density-dependence and selective predation (**Figure 1, Key Figure**) [3-5], suggesting we are only just beginning to understand the role predators play in community disease dynamics.

Research examining how predators modulate host-parasite dynamics has been conducted in both terrestrial and aquatic systems, and the general assumption has been that findings from terrestrial examples are applicable to aquatic systems [6]. While predator-host-parasite interactions in aquatic and terrestrial ecosystems share similarities, there are important differences between aquatic and terrestrial food webs that might influence these interactions. This includes much greater consumption of primary productivity by aquatic herbivores and greater regulation by top-down forces in aquatic food webs [7], as well as longer food chain lengths in aquatic webs [8]. In addition, the properties of marine and freshwater habitats facilitate organism life histories and traits uncommon on land (e.g., an abundance of filter feeders and parasites that are environmentally transmitted), which can generate unexpected pathways by which predators influence parasites in their prey [3, 6, 9]. Conversely, certain parasite life histories that are common in terrestrial systems are extremely rare in aquatic environments – most notably, vector-transmission, as we discuss more below. While a systematic comparison of the strength of different mechanisms in aquatic vs. terrestrial systems is beyond the scope of this review, our hope is that this

synthesis of research on aquatic systems improves our understanding of the ecology of infectious diseases in aquatic food webs.

Aside from providing an important insight into disease ecology, improving our understanding of parasites in aquatic systems is essential to managing disease outbreaks that affect food security (e.g., aquaculture), and human and wildlife health (e.g., schistosomiasis) (**Box 1**). Considering that disease emergence in marine and freshwater environments is predicted to increase with climate change [10], understanding how predation mediates parasites in these systems is critical.

In this review, we examine the mechanisms by which predators mediate host-parasite interactions in their prey, focusing exclusively on aquatic systems. We use a broad definition of the term "parasite", referring to any organism or virus that lives in or on another organism and experiences a fitness benefit while the host organism incurs a fitness cost; thus, in this review, "parasite" encompasses macroparasites and microparasites, including viral pathogens.

Physicochemical properties of aquatic habitats influence parasitism

Physical and chemical properties of water have shaped the evolution of life histories and traits of aquatic organisms, giving rise to biotic interactions that operate via mechanisms that are absent or rare on land [6, 9, 11]. Compared to terrestrial habitats, many aquatic habitats (e.g., lakes, pelagic zones of oceans) provide a relatively stable environment for free-living biota, with lesser fluctuations in temperature, salinity and ultraviolet radiation and a lower chance of desiccation [9, 12]. Water is also approximately 50 times more viscous and 800 times denser than air at a given temperature [12].

While host-to-host parasite transmission is present and even prominent for some taxa such as fish (e.g., cestodes and trematodes), the relative stability of aquatic environments has fostered an abundance and diversity of free-living parasitic agents [9]. These agents are

less dependent or entirely independent of host-to-host contact or vectors for transmission, but instead can either actively swim towards potential hosts (**mobile transmission**, see **Glossary**) or are passively transported by currents [9]. **Passive transmission** is especially significant since parasites can remain suspended in the water column for substantial amounts of time, and can be dispersed quickly by currents [6, 9]. This can support high connectivity between parasite populations, especially in marine ecosystems [6]. However, the same currents that facilitate passive transportation towards potential hosts can move parasites further away from their hosts (including downstream); moreover, passive transportation can move free-living stages to (or trap them in) locations where biotic or abiotic forces can impose mortality.

The life histories and behaviours of aquatic hosts also shape their interactions with parasites. Aquatic environments are home to a relatively high abundance of filter feeding animals [9], which subsist on suspended organic material in the water. Filter feeders are highly vulnerable to passively (and actively) spread parasitic life stages [9]. When infected hosts die on land, in many (but not all) cases, their parasites will also die or at least be contained within a relatively small area that can be avoided by other potential hosts [11, 12]. In aquatic environments, however, parasites released from a deceased and decomposing host may survive for a period in the water column and be transported via currents to viable hosts [13]; one economically important example of this is dermo disease in oysters, where release of spores of this protist parasite is greater from dead than live hosts [13].

Of course, aquatic habitats vary significantly in their geomorphology, hydrology and biodiversity. There is also significant variation within habitats over time that can alter host-parasite interactions [14]. For instance, seasonal stratification in temperate freshwater lakes can impede the movement of infectious spores up and down the water column, as well as host or predator movement [14, 15]. The impacts of predators on parasitism might differ in strongly stratified habitats, as compared to aquatic and terrestrial habitats without strong

104 spatial structuring; one possibility is that, in strongly stratified habitats, predation might
105 promote disease by helping parasites avoid ecological traps (see **Box 2** for an example).
106 Another key feature of aquatic habitats that can vary substantially over time is water
107 volume. This can have important effects on the likelihood of a host encountering a parasite,
108 perhaps especially for filter-feeding hosts. As one example, in intertidal zones, water
109 volume fluctuates multiple times a day, and when it is at its lowest, the concentration of
110 parasitic free agents may be relatively higher, increasing the likelihood of uptake by a host
111 [11]. Similar shifts can occur on somewhat longer timescales in temporary ponds; as they
112 dry seasonally, densities of hosts and free-living parasites should increase, all else being
113 equal. These shifts in the volume of a habitat are more pronounced in (some) aquatic
114 systems than in terrestrial systems, which means the influence of predation on parasitism
115 might vary on relatively short timescales in aquatic systems. Overall, features specific to
116 aquatic habitats can strongly impact how host predators influence parasitism.
117
118 **Mechanisms by which predators influence host-parasite interactions**
119 *Density-mediated indirect effects (DMIEs)*
120 Infectious disease dynamics are strongly tied to host population density [16-18]. In many
121 cases, disease transmission increases with host density, as encounter rates between infected
122 and uninfected hosts rise [19]. When parasite transmission is density-dependent, a **host-**
123 **density transmission threshold** may exist, meaning epidemics are shorter and smaller (or
124 do not occur at all) at low host densities [20]. This occurs even when predators do not
125 preferentially prey on infected prey (a scenario that we discuss more below), for two
126 reasons. First, predators that prey at randomly on host populations will end up consuming
127 some infected hosts; if this does not lead to transmission (e.g., because the predator digests
128 the parasite), this is known as **concomitant predation** and should reduce parasite
129 abundance in the environment. Second, even if predators did not eat any infected hosts, by

preying on the host population, they reduce its density, which should reduce the likelihood (and size) of outbreaks of parasites with density-dependent transmission (left side of **Figure 1A**).

While strongly supported by theoretical work, empirical evidence for host-density thresholds for disease in aquatic systems is relatively scarce, due at least in part to the challenges of observing and accounting for parasite-induced mortality in aquatic wildlife [20]. There are, however, some notable examples in systems with both direct and environmental parasite transmission, including sea lice infestations on farmed salmon [21], bacterial infections in sea urchins [18], and fungal epidemics in *Daphnia* [22].

The host-density threshold is central to the assumption that predators reduce disease in prey populations [1]: by increasing host mortality rates, predators reduce the supply of susceptible hosts, making it more difficult for a parasite with density-dependent transmission to persist in a population. Particularly striking examples of **density-mediated indirect effects (DMIEs)** driving lower transmission come from systems where human intervention has significantly altered predator abundance [18, 23]. For example, a bacterial disease outbreak in sea urchins was found to coincide with an increase in host population following the removal of lobster predators through fishing [18]. However, overall evidence points to DMIEs producing mixed outcomes on parasites in aquatic prey (**Table 1**). Of the three studies in **Table 1** that hypothesized DMIE as the main mechanism underlying impacts of predators on parasitism, two studies (one on a molluscan host, the other on an echinoderm host) found that DMIE did, indeed, lower parasite prevalence [5, 24]. However, the third study (on a crustacean host) did not find an effect of predators on parasite prevalence, hypothesizing that this might have occurred due to very high transmission rates during the study [25]. While much more research is needed to understand the reasons for mixed effects of DMIEs on parasitism, changes in host behaviour linked to anti-predator responses and changes in population density may play a role [5, 24].

156 Parasite dynamics in sessile filter-feeding hosts can also deviate from predictions of
157 the healthy herds hypothesis [9]. Sessile filter-feeding hosts are particularly susceptible to
158 passively transmitted parasites, since they cannot move once established in a location [9].
159 Yet for some diseases, effective transmission requires a sufficiently high infective dose [9,
160 11, 26]. At high host densities, water may be 'over-filtered', driving an encounter-dilution
161 effect [9]. Here, viable parasitic stages are divided between hosts, resulting in a unimodal
162 relationship between host density and disease prevalence [27]. In such scenarios, predator-
163 driven reductions in host density might increase infective doses [9]. However, whether an
164 encounter-dilution effect is observed is also dependent on the dispersal potential of the
165 parasite [27]. If parasites can disperse broadly, as they often do in marine environments [6,
166 9], they are less likely to be impacted by host density at a particular site, illustrating the
167 importance of considering spatial scale as well as host life histories and parasite
168 transmission modes.
169
170 *Trait-mediated indirect effects (TMIEs)*
171 Changes in prey behavioural, morphological and physiological traits that reduce predation
172 risk (**trait-mediated indirect effects (TMIEs)**) are widely reported in the literature and can
173 mediate host-parasite interactions [28-30]. Many aquatic organisms recognize chemical cues
174 released from predators **(kairomones**) and from injured prey (alarm cues) during
175 (attempted) predation events, alerting prey to potential danger [31-33]. While the 'ecology
176 of fear' was first described for terrestrial systems [34], it applies to aquatic systems as well,
177 especially since kairomones and alarm cues can persist in aquatic environments well after
178 the predation event. Numerous studies have taken advantage of this persistence of chemical
179 cues in aquatic environments to study how TMIEs of predators on prey alter parasite
180 transmission prevalence and load; these studies have often used predator kairomones or

caged predators to induce changes in traits, and have particularly focused on amphibian and crustacean hosts (**Table 2**).

There is clear evidence that TMIEs of predators on prey/host behaviour can influence the risk of parasitism. Many prey species lower their activity rates to reduce visibility to predators; this behavioural change can increase or decrease infection prevalence [35, 36]. Prey may also alter habitat use in response to predators, with consequences for infection risk (**Figure 1C**). For example, in some systems, *Daphnia* that shift deeper in the water column in response to fish increase their exposure to parasites on the substrate [28]. In these cases, aquatic prey may find it challenging to avoid both predators and parasites, since reducing the risk from one natural enemy increases the risk from the other; this 'scared sick' phenomenon has also been observed in terrestrial systems [37].

Aside from behavioural anti-predator responses, morphological changes can also mediate how hosts interact with parasites. For instance, many aquatic predators are gape-size limited, and some aquatic prey taxa increase body size upon exposure to predator kairomones [30, 38] – indeed, morphological responses by aquatic prey such as *Daphnia* and tadpoles in response to predator cues are textbook examples of phenotypic plasticity. For filter feeders such as *Daphnia,* increased body size also correlates with a higher filtration rate and a greater probability of infection by some parasites, which are often inadvertently consumed while grazing [30, 39-41]. Again, we see here the conundrum faced by prey when dealing with multiple threats, where a response reducing one threat instead enhances another.

Exposure to caged predators or kairomones has also been shown to alter immune function in aquatic taxa [42]. Anti-predator responses and immune defences can impose significant costs that divert resources from one another, or from growth and reproduction [43]. Yet, whether parasite transmission or load also changes as a result is unknown. Notably, some aspects of the immune response differ between aquatic and terrestrial

organisms; for example, fish and frogs differ from mammals in how they generate and recruit granulocytes (which are involved in the early response to pathogens) [44], and fish and amphibians, unlike terrestrial vertebrates, secrete a mucous cutical comprised of polysaccharides and glycoproteins [45]. Furthermore, the behavioural, morphological, and immunological mechanisms by which predators impact parasites in their prey can be linked, since, for example, a decrease in foraging behaviour may impact immune function (though here, too, relationships can be complicated; [46]). Thus, the significance of this TMIE in the aquatic environment remains to be seen.

Simultaneous DMIEs and TMIEs

Behavioural changes in prey in response to the threat of predation, such as lowered activity levels, can mitigate or enhance DMIEs of predators on parasites [5, 47]. In aquatic systems, there is some evidence that parasite transmission mode might influence whether anti-predator behaviour is associated with increased or decreased disease transmission following predator driven reductions in population density [5, 36]. For example, transmission of ranavirus amongst tadpoles declined primarily due to predator-driven reductions in host density [36]. In contrast, DMIEs of predators on trematode transmission in another tadpole species were counteracted by lowered host activity levels [5]. Indeed, as predator density increased, the number of metacercariae per tadpole also rose [5]. One possible explanation for these differing results is that ranavirus is directly transmitted between hosts, whereas free-living trematode cercariae are mobile and more successful in attaching to immobile than active hosts [48]. Given the abundance of free-living parasitic stages in aquatic environments, more studies should consider how host anti-predator behaviour influences contact rates with parasites.

Other host behaviours may also influence the outcome of DMIEs on parasite transmission and prevalence. Many marine and freshwater taxa, including fish, amphibians,

and crustaceans, respond to the threat of predation by forming schools [49]. In marine habitats especially, species may form highly mobile aggregates, some migratory, potentially spreading disease [6, 17]. For directly transmitted parasites, transmission depends on an infectious individual contacting uninfected hosts [19]; if predators induce swarming behaviour in their prey, this can increase disease spread [50]. Aside from swarming, population density can influence feeding rate. For example, *Daphnia* spp. depress feeding rates at high densities, decreasing the likelihood of encountering environmentally transmitted pathogens [51]. Therefore, infection prevalence may be lowest when *Daphnia* densities are either particularly low or particularly high [51]. These possibilities, as well as others — including the effects of density-dependent investment in immune responses [52] — could alter DMIEs of predation on parasitism.

Effects of selective predation on host-parasite interactions in prey

The healthy herds hypothesis predicts that predators that feed selectively on infected individuals should strongly reduce parasite transmission and prevalence (right side of **Figure 1A**), potentially protecting host populations – that is, selective predation should amplify the healthy herds effect, because, in addition to reducing host density, it preferentially removes infected individuals from the population [1]. There are numerous examples in aquatic systems of selective predation on infected hosts as a result of altered behaviour or appearance. Behaviours associated with disease (sickness behaviours such as decreased activity levels) and manipulation of host behaviour to facilitate transmission to a secondary host can both make prey easier to find and catch [43, 53]. Infections can also make prey more visible to predators. This has been observed in parasitised zooplankton, where uninfected individuals are typically transparent, but infected individuals have altered colour or opacity that makes them more vulnerable to fish predation [2].

Some of the best-known examples of selective predation are those where the parasite is **trophically transmitted** — that is, where it relies on predation of an infected intermediate host by a definitive host to complete its life cycle [54]. Here, we expect predators that are also definitive hosts to facilitate disease in their prey population [54]. However, parasite-induced visual or behavioural changes can both help and hinder transmission [55]. In particular, non-definitive host predators may become attracted to and selectively attack infected hosts, killing the parasite [55].

In some cases, aquatic predators can become infected with parasites of their prey even when the parasite is not trophically transmitted. Studies have reported aquatic predators contracting parasites from prey (e.g., the crab *Carcinus maenas* has been found to harbour a virus that normally infects its oyster prey [56]). Where predators can become infected by the same parasite as their prey, they also face a trade-off, where infected prey may be easier to catch but carry a risk of infection [57].

Outside of trophic transmission, our understanding of selective predation in aquatic systems predominantly comes from models that suggest selection predation will reduce disease transmission and prevalence, buffering host populations from parasite-driven crashes [e.g. 58, 59]. Yet empirical experiments show mixed results, with some showing that predators limit parasitism [60] and others indicating no significant effect of selective predation [25, 61]. First, parasitism does not always influence the likelihood of predation. Second, even when there is selective feeding on infected hosts, it may be mediated by a range of factors, including temperature, seasonality, water clarity, overall mortality rates, and evolution of host-resistance [58, 59, 62-64]. Future empirical studies should ideally account for variation in environmental conditions and host-parasite dynamics to accurately measure the effects of selective predation on parasite prevalence and transmission. It is also crucial to identify if predators that selectively feed on infected prey spread viable spores that go on to infect other hosts, since this could increase transmission [3, 65].

Predation on free-living infectious stages and predation on ectoparasites

While concomitant predation on parasites is most common, there are two important scenarios where predators prey on parasites without also preying on their hosts. First, in some cases, predators feed on free-living infectious stages in the environment (**Figure 1B**). For example, filter feeders can inadvertently ingest infectious stages of parasites of other organisms, as in the case of *Daphnia* inadvertently consuming spores of the amphibian parasite *Batrachochytrium dendrobatidis (Bd)* [66]. The abundance and diversity of free-living infectious stages means they can be a significant source of food for aquatic predators [67]. For example, a study on California killifish found that fish readily eat cercariae of native trematode species in the lab, and found cercariae in the guts of fish collected in a natural estuary, concluding that cercariae might be a common source of energy for these killifish [68]. In some instances, free-living infectious stages can unlock energy transfer pathways between trophic levels previously resistant to predators (e.g., the 'mycoloop' that allows *Daphnia* to indirectly benefit from large, inedible chytrid-infected phytoplankton by feeding on free-living fungal spores [67]). Second, predators can feed solely (or primarily) on ectoparasites without consuming the host to which they are attached, as is the case with cleaner fish and cleaner shrimp that remove ectoparasites [69].

Predation on free-living infectious stages or on ectoparasites should reduce the prevalence and/or intensity of infection in host populations, though increased parasitism after removal of cleaner fish is not always observed [70]. This mechanism has interesting applications, including the addition of cleaner shrimp or fish to aquacultures to control harmful parasites [71] and proposals to manipulate filter feeders to reduce disease [72] including *Bd* in frog populations [73].

In some cases, predators will eat the free-living infectious stages of parasites of their prey and eat the (infected and uninfected) prey as well. Here, predators both consume and

compete with parasites [5] (known as **intraguild predation**). In theory, this should dilute disease in prey populations since predators are reducing the densities of both infective stages and infected hosts (unless parasites are trophically transmitted) [5, 47]. Yet the effects of intraguild predation are complex, varying with predator feeding behaviour and susceptibility to infection, prey quality, and host response [74, 75]. In particular, when faced with free-living infectious stages, infected hosts, and uninfected hosts, predators may face a trade-off between prey nutritional value, catchability, and infection risk [74]. If predators prefer to consume alternative prey or uninfected hosts over free-living infectious stages and/or infected hosts, they may not reduce parasite transmission rates [76]. For example, damselfly larvae have been found to consume and reduce trematode transmission among tadpoles [77]. Yet, in a later study, trematode transmission was higher when damselflies were present, presumably because they opted to feed on zooplankton rather than cercariae [47]. This demonstrates the importance of testing hypothesized impacts in realistic, complex communities, since outcomes may differ from those in simplified communities. Intraguild predation may decrease host population density and so could increase parasite exposure for the remaining hosts [5]. Additionally, it may induce anti-predator behaviours in hosts, further influencing host-parasite interactions [5].

Injuries inflicted by non-lethal predation events

Predator-prey interactions can result in the escape of wounded prey [78, 79], or, in the case of colonial prey (e.g., corals), death and tissue damage to part of the colony [80, 81]. Not only are predator-inflicted injuries energetically costly to the prey, potentially leaving them immunocompromised [82], but damage to protective epithelial tissue can provide entry points for infection [80, 81] (**Figure 1D**). For example, fish that escaped predation attempts by cormorants had higher intensities of infections of ectoparasite species compared to fish protected from predators [78].

Sessile hosts subjected to predation by mobile predators may be especially vulnerable to tissue damage and subsequent infection from environmentally transmitted parasites. Here encounter rates between predators and hosts are high as prey cannot escape [83]. This may help explain why evidence linking predation related injuries and disease in aquatic systems comes almost exclusively from studies of coral diseases (**Table 1**). Numerous taxa prey upon corals, including fish, echinoderms, and molluscs, and many leave lesions open to infection from environmentally transmitted parasites [4, 81, 84]. For instance, lesions left by the crown-of-thorns starfish (*Acanthaster planci*) on corals, which can reach 100 cm² in size, were found to promote the appearance and progression of Brown Band Disease, a widespread affliction caused by bacteria and ciliates [85]. While many parasites are passively transmitted to corals on currents, they can also actively migrate to damaged tissue, showing a preference for lesions compared to healthy polyps [85].

Notably, mechanisms by which predators feed on coral may determine whether corals become infected with diseases such as Brown Band Disease [80, 84]. Corals fed upon by taxa that leave large feeding scars, such as gastropods, echinoderms, and parrot fish, are more likely to contract infections than those that pick at individual polyps, such as butterfly fish [57, 84]. Presumably this is because the latter predator does not cause sufficient tissue damage to initiate infection, although it is also possible that corals redirect energy and resources to healing large feeding scars, leaving them more vulnerable to disease [86]. Either way, identifying predator feeding behaviour and the extent of injury inflicted upon prey would likely help to predict the probability of infection following predation attempts/activity.

Reports of **vector-borne diseases** in aquatic systems are much rarer than in terrestrial systems, possibly because of the extent of long-distance passive dispersal in water and abundance of free-living parasitic agents in aquatic environments [6]. However, there is some evidence that corallivorous predators can act as vectors for disease in their prey [4, 84,

87]. To date, a small number of corallivorous species, all of which are invertebrates, have been identified as vectors of the ciliate and bacterial communities that constitute black and brown band diseases in corals [4, 84, 87]. It appears that these vectors may transmit the pathogens to coral colonies via their faeces or wounds while feeding [4, 84].

Foraging behaviour may be important in determining whether a coral predator vectors disease. While butterfly fish did not transmit brown band syndrome, the snail *Drupella* did, presumably because the fish did not remove enough tissue from the coral to cause a wound, whereas larger snail wounds allow entry of the pathogens [84]. However, there are a range of alterative reasons as to why some predators may be better vectors than others, including variation in host specificity for parasites. A greater understanding of how marine and freshwater predators harbour and transmit parasites back to prey populations would aid in identifying possible vectors that could be controlled to minimize disease spread.

Predators that spread free-living parasitic agents

Predation does not always remove parasites and their infectious stages from the ecosystem. The hospitability of the relatively stable aquatic environment means that infectious agents that survive predation of their host can exist after this event, possibly going on to infect other hosts [3, 65]. Moreover, the flow of water can make it so that predation events spread infectious stages over a considerable distance, as discussed in the previous section. If sufficient numbers of viable infectious agents survive predation and are released, and if this number exceeds that released following the natural death and decay of the host, then predation may increase transmission rates, promoting epidemics [3, 88]. For obligate killing parasites, which depend upon the death and degradation of their host to be released into the environment [89], this method of transmission could be critical, particularly in highly structured habitats such as stratified lakes [3] (see **Box 2, Figure 1E**). The relative hospitability of the aquatic environment as well as the connection between habitats as a

result of flow of water might render predator spreading of infectious stages of parasites more common in aquatic systems than in terrestrial ones; future research evaluating the relative frequency in aquatic vs. terrestrial habitats would be valuable.

Concluding Remarks

Predators modulate host-parasite interactions in aquatic prey via a variety of mechanisms. Research on the impact of predation on parasitism in aquatic systems has played an important role in improving our understanding of how predators mediate parasitism in prey, including providing striking examples of predation increasing disease in prey populations. Ultimately, whether parasitism is increased or decreased depends on a combination of factors including the mechanism operating, predator foraging behaviour, prey life history and parasite transmission mode, among others. One major factor that contributes to predation fuelling parasitism is when predator foraging mode facilitates transmission, as in cases where predators do not completely digest parasite infectious stages (potentially even spreading them in the habitat or to new habitats) and in cases where predator-inflicted wounds make it easier for parasites to infect a host. A particularly striking aspect of many aquatic host-parasite systems is the prevalence of environmental transmission; this reduces the importance of direct contact between hosts, and likely also explains why vector transmission is rare in aquatic systems.

Here we reviewed evidence for the known mechanisms by which predators affect aquatic parasites. However, it is very possible that there are more ways in which predators exert effects on host-parasite interactions that have not been recorded or even explored yet (see **Outstanding Questions**). For example, we do not know if predators can impact parasites by driving trophic cascades [2]. Additional mechanisms, such as predators that act as vectors, need to be examined further. We also lack knowledge on how parasite diversity is impacted by natural predators (but not for fishing, see **Box 3**).

We would also benefit from greater focus on predator traits, especially foraging/feeding behaviour. In a number of the predator-host-parasite systems, predator feeding behaviour interacts with transmission mode to modulate parasite spread (e.g., predator inflicted wounds which increase infection in corals [84]). Developing a stronger understanding of how predator traits intersect with host-parasite dynamics could help us to better predict the consequences of predator introduction or restoration on parasite populations and disease.

It is also apparent that individual predator species can have conflicting or complementary effects on parasite prevalence and transmission via multiple mechanisms. For instance, in some systems, trait-mediated indirect effects can cancel out density-mediated indirect effects (e.g., trematode-tadpole-dragonflies [36]). Most studies measure lethal or non-lethal effects separately, since their effects can be difficult to disentangle. Similarly, only a handful of empirical studies have used multiple predator species (some of which are also alternative hosts) [47, 77]. Yet the joint effects of multiple occurring mechanisms and species can yield unexpected results and needs to be further explored. Whether DMIEs or TMIEs may dominate subsequent effects of host-parasite interactions in a particular system is likely to be mediated by parasite transmission mode and whether TMIEs (especially host behaviour) facilitate increased or decreased transmission. Aquatic systems are ideal for comparing the relative importance of DMIEs and TMIEs – in many, it is possible to manipulate density directly, as well as to manipulate predation levels and/or predator infochemicals. The relative importance of DMIEs vs. TMIEs in driving the outcome of host-parasite interactions, especially in systems where an unhealthy herds effect is observed, is an area ripe for future research.

Finally, predator-host-parasite interactions operate in a changing world and will shift under new environmental conditions. Due to climate change, many aquatic habitats will experience increased salinisation, temperature and acidification, among others, and these

factors can alter the outcomes of predator-host-parasite interactions [62, 90]. We thus need to better understand whether and how the mechanisms identified above will be impacted by global change. Individual species will no doubt differ in the extent to which they are impacted by novel conditions. Predicting the effects of such changes on parasite-host-predator interactions will prove complex, but incorporating changing environmental conditions is critical to understanding how predators mediate parasite-host interactions.

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Declaration of Interests

The authors declare no competing interests.

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735

Glossary

Concomitant predation: when a predator consumes and digests a parasite that is attached to or contained within its host (the prey).

Density-mediated indirect effects (DMIEs): in the context of parasite-host-predator interactions, when a predator induces shifts in the parasite population via changes in the host population density.

Host-density transmission threshold: the minimum host population density below which parasites cannot be transmitted between hosts.

Intraguild predation: when a predator consumes and also competes with another species.

Kairomone: a chemical that is released by an organism and used by an organism of a different species to gain information (e.g., prey detecting the presence of a predator via secondary metabolites it releases into the environment).

Mobile transmission: the active movement of a parasite in its environment (e.g., swimming).

Passive transmission: the movement of infectious stages by environmental features such as currents.

Trait-mediated indirect effects (TMIEs): Changes in prey traits including behaviour, morphology or physiology in response to the threat of predation that induce shifts in the parasite population.

Trophic transmission: when a parasite depends on consumption by a predator of its host to complete its life cycle.

Vector-borne disease: an infection that is transmitted by another organism into a host.

Box 1. Can restoring predators control schistosomiasis in humans?

Schistosomiasis is a disease caused by trematodes of the genus *Schistosoma*. Affecting 220-240 million people worldwide [91], schistosomiasis can impede childhood development and lead to chronic diseases of the gastrointestinal, urinary and central nervous systems [91]. As such, it constitutes a major public health challenge.

Schistosome cercariae infect humans through contact with freshwater; once within the body, cercariae produce eggs that are then shed through urine or faeces [91]. Upon entering a water source, the eggs hatch and, as miracidia, penetrate and infect their intermediary hosts — aquatic snails [23] — with different species of *Schistosoma* showing specificity for different intermediary host genera [91].

Over decades, numerous sites in sub-Saharan Africa have reported that increases in schistosome infection were associated with overfishing of molluscivorous fish or damming, since dams can block the migration of natural predators [92, 93]. Thus, correlative evidence suggested there was a link between the presence of molluscivorous predators which suppressed aquatic snail populations and schistosomiasis prevalence in human populations [93].

Testing the effects of predator restoration on schistosomiasis prevalence in humans on a large scale is challenging given that it requires study of multiple communities adjacent to water sources. Yet, data from a pilot study that compared schistosomiasis prevalence in two Senegalese villages suggest predator restoration could reduce disease transmission to humans [23]. Here, the introduction of a prawn predator (*Macrobrachium vollenhovenii*) into one of the village's river access areas led to a significant decrease in schistosomiasis infections in the community compared to a matched village where no predators were introduced [23]. Additional research has shown infected snails show reduced anti-predator responses and compromised movement, and are selectively consumed by *M. vollenhovenii* [94].

785 Currently, strategies to control schistosomiasis include improved sanitation, access to
786 clean water, drug treatments and snail control [95]. The efficacy of predators as biological
787 controls can vary significantly between locations, due to differences in species assemblages
788 and vegetation [96], and needs to be carefully tested before attempts at restoration. Yet
789 research suggests the most successful attempts at reducing schistosomiasis appear to have
790 relied on a combination of approaches, such as combining snail control with drug treatments
791 [95]. Recent work has focused on identifying areas of high schistosomiasis infection risk
792 using environmental indicators of snail habitat, thus facilitating more effective targeted use
793 of snail control and drugs [97].
794

795 **Box 2. Case study: *Chaoborus-Daphnia*-fungal parasite interactions**

796 Support for predation-spreading of infectious material comes from zooplankton in
797 Midwestern lakes in the US that co-exist with a larval insect predator, *Chaoborus* spp.
798 (**Figure I**). After consuming *Daphnia*, *Chaoborus* regurgitate the carapace, releasing
799 infectious spores of a fungal parasite into the water column (**Figure 1E)**, where they can be
800 taken up by other *Daphnia* via filter feeding [3]. Importantly, the number of viable spores
801 released into the water following *Chaoborus* predation exceeds that following the natural
802 death of the host and, when comparing across lakes, there is a positive correlation between
803 *Chaoborus* density and infection prevalence [3].
804 Habitat structure also influences how *Chaoborus* spread disease. The bodies of
805 infected *Daphnia* that avoid predation sink through the water column, settling on the
806 substrate, where they break down and release spores [98]. In summer, lakes in temperate
807 regions are stratified, meaning these spores are less likely to infect *Daphnia* hosts, which
808 reside predominantly in higher sections of the water column [3]. *Chaoborus* predation on
809 *Daphnia* can circumvent this ecological trap for the fungus, releasing spores near uninfected
810 hosts [2, 3, 65]. This system illustrates how the effect of predators on disease dynamics in

811 prey depends on the intersection between predator feeding behaviour (regurgitation of prey
812 by *Chaoborus*), host feeding behaviour (filter feeding), epidemiology (environmental
813 transmission of spores), and environmental characteristics (a stratified aquatic environment).
814

815 **Figure I (in Box 2). The *Chaoborus-Daphnia*-fungus system.** Predation by *Chaoborus* on
816 fungal-infected *Daphnia* releases infectious spores in the upper well-mixed layer of the
817 water column, where the spores can be consumed by uninfected hosts. In lakes with
818 fewer *Chaoborus*, infected *Daphnia* are more likely to die from virulent effects of the
819 parasite; these *Daphnia* settle down to the sediment prior to releasing spores, which are then
820 trapped near the sediment-water interface where they are less likely to be ingested by
821 uninfected hosts. In the figure, solid yellow *Daphnia* represent infected *Daphnia*. In panel
822 A, spores are shown being released from two infected *Daphnia* that are being preyed upon
823 by *Chaoborus*; other spores are being ingested by uninfected *Daphnia* in the upper mixed
824 layer (epilimnion). In panel B, the dead infected *Daphnia* have settled to the bottom of the
825 lake prior to releasing spores.

826

827 **Box 3. Comparing the effects of natural predators and fishing.**
828 Fishing and harvesting can have different effects on host-parasite interactions than
829 predators. For example, dense populations in aquaculture facilities can facilitate parasite
830 transmission [17]. Conversely, selective removal of larger fish, which are often preferred
831 and often have higher parasite loads, may suppress parasite populations [99].
832 Fishing can reduce parasite diversity and abundance [100-103]. However, while
833 directly transmitted parasite prevalence tends to increase in fished zones, trophically
834 transmitted parasite prevalence decreases [100, 102]. For directly transmitted parasites,
835 fishing may cause individual hosts to encounter more parasites after host population

836 decreases. In contrast, trophically transmitted parasites may be unable to complete their life
837 cycles due to the removal of intermediate or definitive hosts [100]. While more research is
838 needed, trophically transmitted parasites may be more impacted by fishing than predation,
839 as some fishing practises can drive large changes in host assemblages [100]. In comparison,
840 most predators do not have such a wide impact, although it would be interesting to explore
841 effects of native and introduced predators on parasitism.

842 Some predators do not entirely remove infectious propagules from the environment
843 and can spread them to new hosts (**Box 2**). In contrast, since fishing removes the host and
844 parasite entirely from the environment, it likely removes parasites from the system.
845 However, in some cases, fishing practices can facilitate the transmission of trophically
846 transmitted parasites to definitive hosts. For example, fish infected with a trematode parasite
847 are commonly discarded by fisheries, and these discards become available to a seabird
848 predator that is the definitive host of the parasite [104].

849 As in terrestrial systems, culling has been explored in aquaculture as a means of
850 curbing parasite infections [105, 106]. The few studies that have explored the effects of
851 culling on host-parasite interactions suggest it may reduce parasite transmission in teleost
852 and molluscan hosts [105, 106]. Interestingly, while culling led to a decrease in tapeworm
853 transmission in Arctic charr (*Salvelinus alpinus*), this was due to a combination of fishing-
854 driven changes in host population age structure and increased predation by trout, rather than
855 density-dependent transmission [105]. Culling is essentially very intense predation that
856 attempts to control disease, making it a test of the healthy herds hypothesis. Examples like
857 that of the Arctic charr shows that culling can impact host-parasite interactions via
858 unexpected mechanisms (as has happened in terrestrial systems, where culling sometimes
859 increases disease [107]), highlighting the need for future research.
860

861 **Table 1. Effects of lethal predators on parasites.**

Host	Parasite/Pathogen	Predator	Parasite Prevalence	Parasite Load	Transmission/ Progression Rate	Mechanism (s)	Reference
Protista							
Paramecium caudatum	*Holospora undulata* (Bacteria)	*Didinium nasutum* (Ciliophora)	-	-	-	DMIE, TMIE	[108]
Insecta							
Anopheles coluzzii	*Plasmodium falciparum* (Protozoa)	*Anisops jaczewskii* (Insecta)	-	-	-	TMIE	[109]
Crustacea							
Daphnia dentifera	*Metschnikowia bicuspidata* (Fungi)	*Chaoborus americanus* (Insecta)	-	-	Higher	Predator Spreading	[88]
D. dentifera	*M. bicuspidata*	*C. americanus*	-	-	Higher	Predator Spreading	[3]
D. dentifera	*M. bicuspidata*	*Lepomis macrochirus* (Teleostei)	No effect	-	-	DMIE	[25]
Eurypanopeus depressus	*Loxothylacus panopaei* (Crustacea)	Multiple spp. (Teleostei, Crustacea)	Higher	-	-	Unknown	[110]
Echinodermata							
Strongylocentrotus spp.	*Vibrio* (suspected) (Bacteria)	*Semicossphyus pulcher* (Teleostei) *Pycnopodia helianthoides* (Echinodermata)	Lower	-	-	DMIE	[18]

		Panulirus interruptus (Crustacea)					
Mollusca							
Crassostrea gigas	OsHV-1 uVar (Virus)	*Carcinus maenas* (Crustacea)	Higher	-	-	Predators as vectors	[56]
C. virginica	*Perkinsus marinus* (Protozoa)	*Panopeus herbstii* (Crustacea)	No effect	-	-	Unknown	[111]
	Haplosporidium nelsoni (Protozoa)	*Callinectes sapidus* (Crustacea)					
Bulinus spp.	*Schistosoma haematobium* (Trematoda)	*Macrobrachium vollenhoveni* (Crustacea)	Lower	-	-	DMIE	[23]
Cnidaria							
Montastraea faveolata	*Phormidium corallyticum* (Bacteria)	*Chaetodon capistratus* (Teleostei)	-	-	Higher	Predator inflicted injury	[80]
Orbicella annularis	Multiple spp. (Bacteria)	*Coralliophila abbreviata* (Mollusca)	-	-	Higher	Predator inflicted injury	[86]
A. cervicornis	Multiple spp. (Bacteria)	*C. abbreviata* (Mollusca)	-	-	Higher	Predator inflicted injury/	[87]
		C. caribaea (Mollusca)	-	-	No effect	Vector	
Acropora hycacinthus	Multiple spp. (Bacteria)	*Acanthaster planci* (Echinodermata)	Higher	-	Higher	Predator inflicted injury	[85]

A. muricata	Multiple spp. (Bacteria)	*Chaetodeon aureofasciatus*	-	-	No effect	Predator inflicted injury	[112]
		(Teleostei)	-	-	Higher		
		Drupella spp. (Mollusca)					
A. muricata	Multiple spp. (Bacteria)	*C. aureofasciatus*	-	-	No effect	Predator inflicted injury	[84]
		Drupella spp.	-	-	No effect		
A. muricata	Multiple spp. (Bacteria)	*Chaetodeon plebeius*	-	-	No effect	Selective Predation	[61]
		(Teleostei)					
A. cytherea	Multiple spp. (Bacteria)	*A. planci*	Higher	-	-	Predator inflicted injury	[81]
A. hyacinthus	Multiple spp. (Bacteria)	*Cymo melanodactylus*	-	-	Lower	Selective Predation	[60]
		(Crustacea)					
Oculina patagonica	*Vibrio shiloi* (Bacteria)	*Hermidice caranculata*	-	-	Higher	Predators as Vectors	[4]
		(Mollusca)					
A. cervicornis	Multiple spp. (Bacteria)	*C. abbreviata*	-	-	Higher	Predator inflicted injury	[113]
Amphibia							
Rana sylvatica	*Echinostoma trivolvis*	*Ambystoma jeffersonianum*	-	-	-	Unknown	[114]
	(Trematoda)	(Amphibia)					
R. pipiens	Ranavirus (Virus)	*Anax* spp. (Insecta)	Lower	No effect	-	DMIE and TMIE	[36]
Hyla versicolor			Lower	No effect	-		
Rana clamitans	Multiple spp. (Trematoda)	*Ischnura verticalis*	No effect	-	-	Unknown	[5]
		(Insecta)					
Teleosti							

Cyprinus carpio	Multiple spp. (Monogea, Ciliophora, Crustacea).	*Phalacrocorax carbo sinensis* (Aves)	No effect	Higher	-	Predator inflicted injury	[78]
Poecilia reticulata	*Gyrodactylus* spp. (Monogea)	Multiple spp. (Teleostei)	Higher	-	-	TMIE	[115]

This table includes empirical cases where aquatic hosts were exposed to a live predator and parasite. In order to be included in this table, a study needed to focus on predators that consume both the host and parasite, not the parasite only. In addition, studies needed to provide data on a) parasite prevalence in a host population, 2) parasite load, and 3) transmission or progression rate or a parasite or disease. See supplemental **Box S1** for additional details on review methodology, including search terms.

865 **Table 2. Effects of non-lethal predators, alarm cues and kairomones on parasites.**

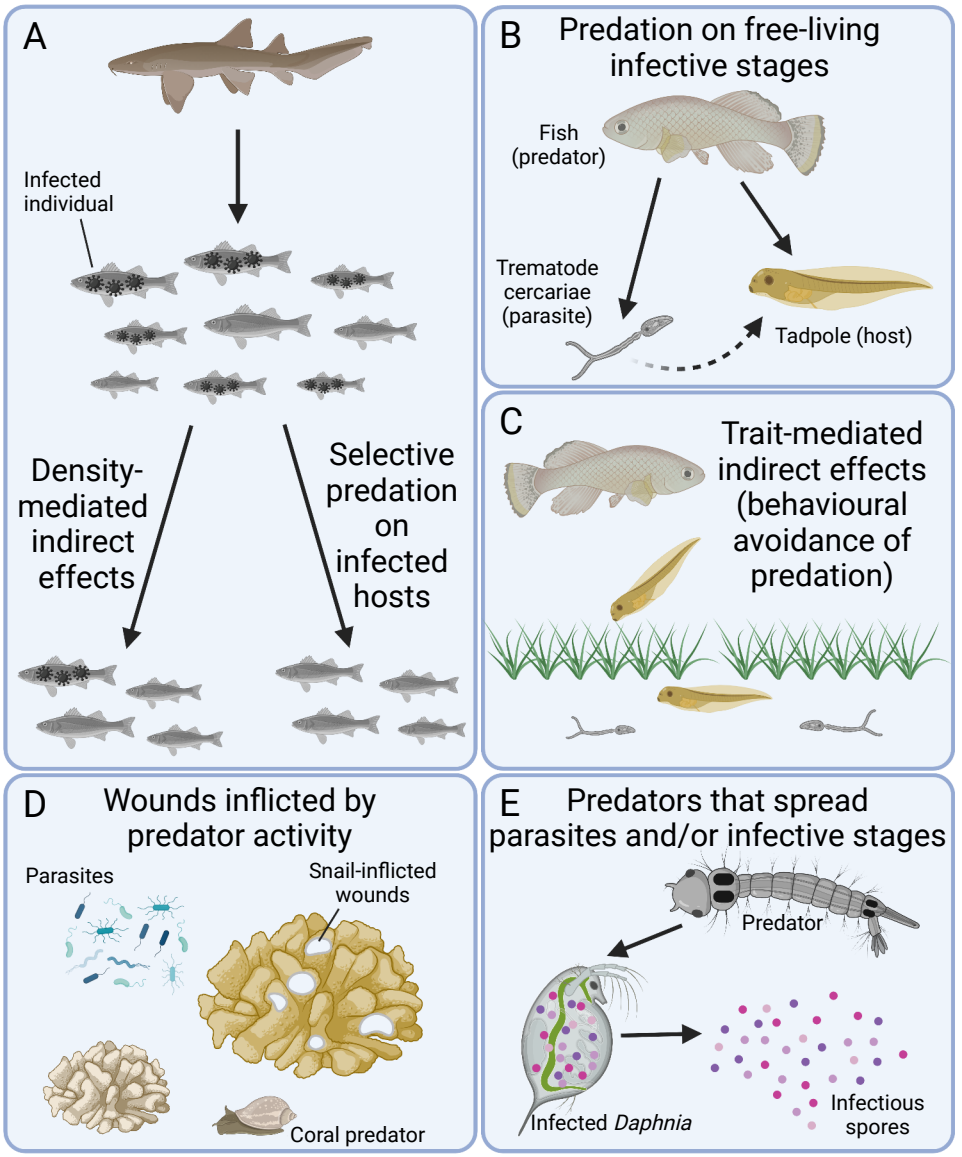
Host	Parasite	Predator	Infection prevalence	Parasite Load	Transmission/ Progression Rate	Mechanism(s)	References
Crustacea							
Daphnia magna	*Pasteuria ramosa* (Bacteria)	*Chaoborus crystallinus* (Insecta)	-	-	-	TMIE	[116]
D. magna	*P. ramosa* (Bacteria)	*Leuciscus idus* (Teleostei)	Higher	-	-	TMIE	[28]
D. dentifera	*M. bicuspidata* (Fungi)	*C. americanus* (Insecta)	More susceptible	Mixed	-	TMIE	[40]
D. magna	*Metschnikowia* spp. (Fungi)	*Rhodeus amarus* (Teleostei) *Triops cancriformis* (Crustacea)	-	No effect	-	TMIE	[117]
D. magna	*Pasteuria ramosa* (Bacteria)	*Leuciscus idus* (Teleostei)	No effect	No effect	-	TMIE	[118]
D. galeata	*Caullerya mesnili* (Protozoa)	*L. idus* (Teleostei)	-	-	-	TMIE	[119]
D. longispina	*Metschnikowia* spp. (Fungi)	*R. seiceus amarus* (Teleostei)	Higher	Higher	-	TMIE	[30]
Amphibia							
Lithobates sylvaticus	*Echinostomatidae* (Trematoda)	*Enallagma* spp. (Insecta) *Anax junius* (Insecta)	-	Higher	-	TMIE	[120]
Rana pipiens *Hyla versicolor*	*Ranavirus* (Virus)	*Anax* spp. (Insecta)	No effect No effect	No effect No effect	- -	TMIE	[36]

L. sylvaticus	*Batrachochytrium dendrobatidis* (Bacteria)	*Dysticus* spp. (Insecta) and conspecific cue	-	Lower	-	TMIE	[121]
Lithobates clamitans	*Ranavirus* (Virus)	*A. junius* (Insecta)	No effect	No effect	-	TMIE	[122]
L. sylvaticus		*Belostoma flumineum*	No effect	No effect	-		
Pseudacris feriarum		(Insecta)	No effect	No effect	-		
H. chrysoscelis			No effect	No effect			
Ambystoma tigrinum melanostictum	*Ambystoma tigrinum* virus (ATV) (Virus)	*A. junius* (Insecta)	-	-	-	TMIE	[123]
Anaxyrus americanus	*Echinoparyphium* spp. (Trematoda)	*Anax* spp. (Insecta)	-	Higher	-	TMIE	[124]
R. clamitans	*Echinostomatidae* spp. (Trematoda)	*A. longipes* (Insecta) *A. junius* (Insecta)	-	No effect	-	TMIE	[125]
R. sylvatica	*Echinostomatidae* spp.	*A. longipes* (Insecta)	-	-	-	TMIE	[126]
R. clamitans		*A. junius* (Insecta)	-	-	-		
Bufo americanus	*Echinostoma trivolvis* (Trematoda)	*Notophthalmus viridescens* (Amphibia)	No effect	No effect	-	TMIE	[127]
R. sylvatis	*E. trivolvis*	*Lepomis gibbosus*	-	Higher	-	TMIE	[128]
R. clamitans		(Teleostei)	-	No effect	-		
R. catesbeianus			-	No effect	-		
R. sylvatica	*E. trivolvis*	*Fundulus diaphanous*	-	No effect	-	TMIE	[35]
R. clamitans		(Teleostei)	-	Higher	-		

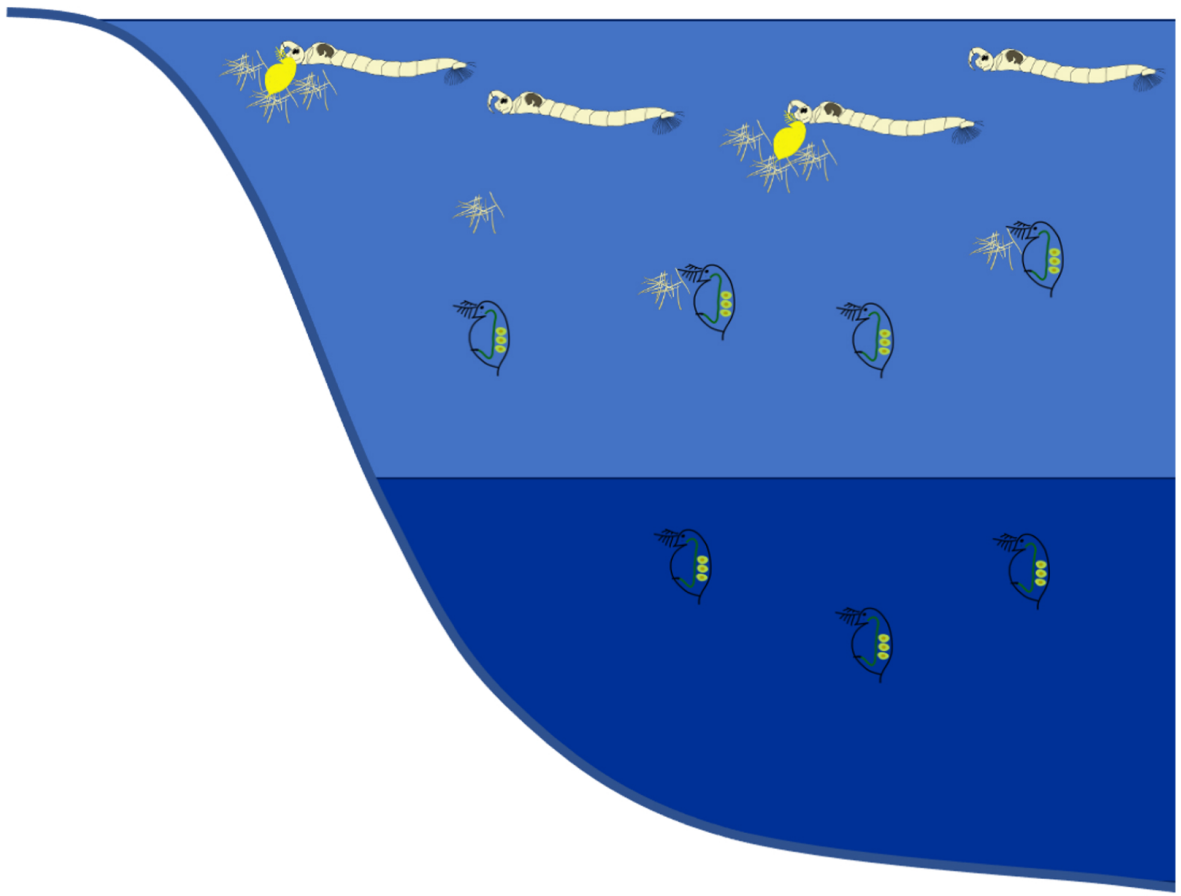
P. regilla	*Ribeiroia ondatrae* (Trematoda)	*Enallagma* sp. *Lestes* sp.	-	-	Higher	TMIE, DMIE	[47]

The table reviews empirical cases where aquatic hosts were exposed to predator cues (alarm cues or kairomones) and a parasite. Studies needed to provide data on a) parasite prevalence in a host population, 2) parasite load, and 3) transmission or progression rate or a parasite or disease in order to be included in this table. See supplemental **Box S1** for additional details on review methodology, including search terms.

Figure 1, Key Figure. Mechanisms by which predators mediate parasite-host interactions in aquatic prey. The main mechanisms by which predators mediate host-parasite interactions in aquatic prey are (A) density-mediated indirect effects and selective predation on infected prey, (B) consuming free-living infectious stages and their hosts, (C) trait-mediated indirect effects, including behavioural changes, (D) inflicting wounds that become infected, and (E) spreading parasites and/or infective stages. Created with Biorender.com.


A
Infected individual
Density-mediated indirect effects
Selective predation on infected hosts
B
Predation on free-living infective stages
Fish (predator)
Trematode cercariae (parasite)
Tadpole (host)
C
Trait-mediated indirect effects (behavioural avoidance of predation)
D
Wounds inflicted by predator activity
Parasites
Snail-inflicted wounds
Coral predator
E
Predators that spread parasites and/or infective stages
Predator
Infected Daphnia
Infectious spores

A) Predation by *Chaoborus* on infected *Daphnia* releases infectious spores in the well-mixed part of the water column where they are more likely to be consumed by uninfected *Daphnia.*



B) Lower predation rates mean infected hosts are more likely to die from infection and sink to deep water prior to releasing spores near the sediment-water interface.