Managing the threat of infectious disease in fisheries and aquaculture using structured decision making

Brian J Irwin[1*], **Megan M Tomamichel**[2], **Marc E Frischer**[3], **Richard J Hall**[2,4], **Alaina DE Davis**[5], **Thomas H Bliss**[6], **Pejman Rohani**[2,4], **and James E Byers**[2]

Fisheries and aquaculture provide food and economic security, especially in the developing world, but both face challenges from infectious disease. Here, we consider management of disease issues from a structured decision-making perspective to examine how infectious disease can threaten seafood production and influence management decisions. For both wild fisheries and aquaculture, disease-management objectives generally aim to mitigate the severity and economic burden of outbreaks. General management strategies include manipulating host densities, reducing system connectivity, conserving or improving habitat, and implementing direct treatments or some other biological interventions. To inform decisions, mathematical models can be used to explore disease dynamics and to forecast the potential effectiveness of alternative management actions. Developing and implementing disease-management strategies also involve considering uncertainties and balancing competing stakeholder interests and risk tolerances. We conclude by outlining several steps for applying structured decision making that are broadly useful to decision makers facing issues related to disease.

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Infectious diseases present a persistent threat to food security and sustainability because they can reduce the production, yield, and marketability of harvested goods (Lafferty *et al.* 2015; Ristaino *et al.* 2021). In aquatic systems, pathogens can spread rapidly through populations and be transported over large distances, and bidirectional transmission between cultured and wild populations is possible (Harvell *et al.* 1999; Lafferty *et al.* 2004; Krkošek 2017). Fishery and aquaculture managers already face a major challenge in keeping up with the demand for seafood (Rosenberg 2003; Ripple *et al.* 2019; Zeller and Pauly 2019; FAO 2020), and management decisions are likely to be even more complicated when the combined effects of harvest and disease lead to population declines (Wilberg *et al.* 2011). To meet these challenges, scientists, stakeholders, and managers can work across disciplines to evaluate options, produce defensible decisions, and reduce losses caused by infectious disease.

In a nutshell:

- Infectious diseases influence population dynamics and the value of seafood products
- Structured decision making can be used to organize available information, identify quantifiable objectives, and evaluate alternatives for disease management
- To date, management strategies have aimed to adjust host density, reduce disease transmission, or improve host health; however, specific alternative actions for wild-capture fisheries and aquaculture systems may vary in availability and effectiveness
- Within a decision-making process, mathematical modeling of host–pathogen dynamics can be integrated into management strategy evaluation to produce scenario forecasts and sensitivity analyses needed for trade-off and risk analyses

We approach disease management for seafood production in the context of structured decision making. Although we primarily adhere to language familiar to practitioners of structured decision making, the perspective carried through this article parallels attributes of other actionable processes, including management strategy evaluation, integrated pest management, strategic habitat conservation, and adaptive governance. Our organizational structure is similar to the "PrOACT" (problem, objectives, alternatives, consequences, trade-offs) concept, which Hammond *et al.* (1999) used to emphasize proactiveness when approaching a decision. We identify several general types of management alternatives and specific actions that sometimes differ in applicability between open aquatic systems and more controlled aquatic systems such as aquaculture. The evaluation of management strategies is increasingly

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[1]*US Geological Survey, Georgia Cooperative Fish and Wildlife Research Unit, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA* [*]*(irwin@uga.edu);* [2]*Center for the Ecology of Infectious Diseases and the Odum School of Ecology, University of Georgia, Athens, GA;* [3]*Skidaway Institute of Oceanography, University of Georgia, Savannah, GA;* [4]*Department of Infectious Diseases, College of Veterinary*

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model-based, and we briefly review how disease dynamics might be incorporated into scenario forecasts to predict potential consequences for harvested species. We highlight how some decision-relevant uncertainties might be heightened by infectious diseases, and note that some uncertainties might be effectively reduced through research, management, and monitoring actions. Finally, we discuss how uncertainties may translate into risks for a decision maker and how differing or dynamic risk tolerances might affect evaluations of available options for achieving sustainable seafood production.

Structuring a decision problem

Generally speaking, managers implement policies and regulations to achieve stakeholder objectives or agency mandates. In doing so, they act as decision makers, who are likely to rely on imperfect information and encounter constraints that limit what can actually be accomplished. Traditionally, management of fisheries and aquaculture has operated as an extraction or production problem, driven by expectations for harvesting or producing sellable yields. Consequently, much of modern fisheries management centers on performance of harvest strategies (Smith *et al.* 2008; Dowling *et al.* 2015) and may include explicit evaluation of alternative "control rules" for determining allowable take (Deroba and Bence 2008; Wiedenmann *et al.* 2013). In particular, "management strategy evaluations" for several fisheries demonstrate how alternative management strategies can be considered relative to their ability to meet objectives (Punt *et al.* 2016; Feeney *et al.* 2019). Structured decision making is a similar process of decomposing a decision problem into more workable parts, which include specifying objectives, evaluating alternatives, and confronting uncertainties and trade-offs (Irwin *et al.* 2011; Conroy and Peterson 2013). In the context presented here, we frame the decision problem as the following: managers are attempting to implement strategies that achieve sustainable harvest while considering numerous uncertainties or mitigating potential losses, including those influenced by disease. From this, a decision process can proceed to specifying objectives and evaluating the anticipated performance of alternative management options while accounting for relevant information gaps.

Specifying and organizing objectives

For fisheries and aquaculture, objectives often relate to harvest or production, including maximizing yield or minimizing variability of yield (or the associated economics) over time. For instance, Brown and Mumby (2014) specified that a fishery goal is to maximize long-term profits aggregated across populations; they also defined a conservation objective as "maximizing the number of habitat patches where the fish community meets or exceeds" established precautionary reference points related to biomass of species groups. Similarly, Behringer *et al.* (2020) identified three aims of managing disease through fishery regulations: (1) maintaining or improving the stock, (2) limiting or reducing disease proliferation, and (3) protecting human health.

A key characteristic of decision objectives is that they are value-based. In other words, objectives represent what is fundamentally important to the decision maker for that decision (Hammond *et al.* 1999). For this review article, we view an overarching "fundamental objective" (see below for additional context): "provide safe and sustainable seafood". This high-level objective reflects values about human safety, temporal variability in harvests, population viability, and product marketability. Within a given decision context, an objective is sometimes distinguished either as "fundamental", if it indicates why a decision is important, or as "means", if it indicates how a fundamental objective may be achieved (Keeney 1996). In this regard, determining how to achieve the fundamental objective of safe and sustainable seafood may be assisted by articulating disease-management alternatives through an objectives hierarchy that includes subordinate means objectives (eg "reduce parasite-induced damage"). As a starting point, we illustrate how disease-related objectives could be incorporated into decision support alongside conservation- or harvest-focused objectives (Figure 1). Alternatively, for some fisheries, disease-related means objectives might be subordinate to other means objectives focused on harvest or stock rehabilitation. Such organization would imply that avoiding or mitigating disease was important via its potential to limit harvests or production rather than independently important in its own right.

Identifying alternative management actions

Despite at times sharing similar objectives, fisheries and aquaculture systems more often have distinct management approaches or specific regulations. Even so, we developed a broad classification of general strategies for disease management or mitigation (Table 1), which can facilitate identification of more specific alternative actions that could be evaluated based on the potential for producing benefits to humans and safeguarding the persistence of the target population. These strategies largely attempt to influence disease transmission rates by affecting host density, reducing system connectivity, or improving host health. Within these categories, specific alternative actions can vary based on the level of management control relative to environmental influences and stochasticity.

Management strategies that manipulate population density through harvest or other means typically include actions that are expected to reduce pathogen transmission by lowering stock density. For instance, harvest alternatives may differ in the extent they reduce population density, which could alter the frequency of contacts between infected and uninfected hosts (ie "fishing out" parasites; Dobson and May 1987; Wood *et al.* 2010). Likewise, managers may

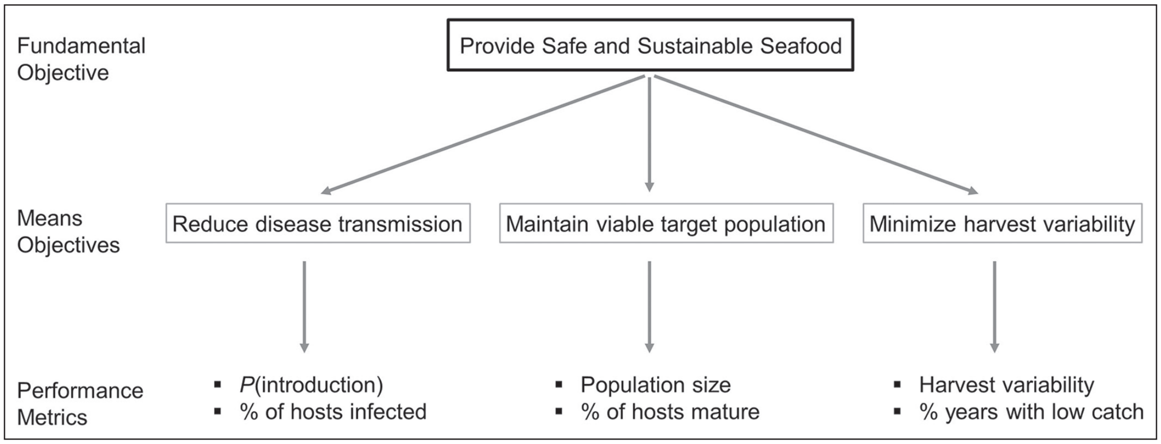

Figure 1. An objectives hierarchy, depicting a fundamental objective (ie values that indicate importance) connected to subordinate means objectives (ie how to achieve) and performance metrics to summarize consequences. In this example, performance metrics include the probability of introducing a pathogen, the percentage of infected hosts observed through monitoring, the estimated abundance of the target population, the percentage of the host population that has reached maturity, the interannual variability in harvests, and the percentage of years when harvests are below a target reference point.

manipulate a different host in a parasite's life cycle in an attempt to benefit the species targeted for harvest (Hedegaard Clausen *et al*. 2012). Stock enhancements have also been used in attempts to increase population densities, but translocation of animals can also introduce disease risks associated with both the introduction of disease agents and reduced genetic variability of the stock (Lafferty *et al*. 2015). Alternatives that influence host density could affect both infection containment and harvest sustainability and thereby relate back to multiple objectives.

Some management strategies focus on manipulating system connectivity to create a spatial or temporal barrier to reduce the spread of an infection. Fishing exclusion zones generally attempt to spatially control where harvests occur (Byers and Noonburg 2007), and area closures have been used in response to a viral outbreak in an effort to minimize

Table 1. Alternatives for managing or mitigating disease for safe and sustainable seafood

General strategy **• Alternative management actions**	**• Examples of specific tactics**
Manipulate density or demographics	
• Harvest or production policies • Stocking plans • Selective or mandatory harvest regulations	• Adjust host density to lower intra-system transmission rates • Reduce aquaculture production to minimize disease outbreak • Select for sizes most vulnerable to disease or cull “sick” individuals
Alter system connectivity	
• Prevent species invasion • Fishing exclusion zones • Minimize inter-system transmission • Eliminate cross-system stocking • Disconnect aquaculture from wild stocks • Quarantine	• Use physical barriers to block spread • Avoid or ban access to disease-prone or infected areas • Gear sterilization or dedicated use • Mandate testing prior to movement of animals • Regulate ballast water discharge • Prohibit entry during a disease outbreak
Modify habitat	
• Improve water quality • Limit conditions favorable for disease • Introduce artificial spawning areas or aggregation devices	• Create cool-water pool habitat to inhibit pathogens • Pond drainage to eliminate unwanted organisms • Restore or develop reefs
Implement direct treatment	
• Apply chemotherapeutants • Vaccination • Temperature manipulation	• Batch or feed-based treatments • Vaccinate individuals to stimulate immune response • Alter thermal regime to depress parasite load or alter infectious period
Implement biological intervention	
• Modify food web or species composition (biocontrol) • Selective breeding	• Stocking hosts selected for disease tolerance • Stock predators of parasite • Preserve genetic diversity / select for rapid growth (manage growth to achieve reproduction to “outpace” disease)

spread (Prince *et al.* 2008). In addition, fishing gear or other possible vectors might be disinfected or separated for use between locations to help minimize unwanted transmission, such as in the control of invasive species (Holeck *et al.* 2004). Manufactured barriers that prevent movement of wild organisms are a more severe form of altering system connectivity (Zielinski *et al.* 2019), although this option is perhaps most plausible in freshwater systems or aquaculture. Alternatives such as quarantine could also reduce the probability of pathogen introduction, but these require a level of population control that may only be feasible in aquaculture systems (Behringer *et al.* 2020).

Other strategies attempt more direct approaches to alter disease dynamics or improve host health. For instance, some alternatives focus on improving habitat quality, which may limit conditions favorable to disease, whereas other alternatives may instead attempt to improve disease tolerance of the hosts. Shellfish are sometimes relocated to cleaner habitats for depuration that purges contaminants, thereby improving palatability and reducing pathogen and contaminant loads to human consumers (Lees *et al.* 2010). Likewise, direct treatment can alter community or age composition, such as with the application of lampricides to reduce parasite load (Irwin *et al.* 2012). The use of biocontrol options, such as cleaner fish, may be an option for some systems. More recently, manipulating the gene pool to affect fitness or improve disease resistance is an approach increasingly under consideration by managers (Buck *et al.* 2020).

Modeling approaches to support disease management

Within PrOACT, models are used to predict the consequences of management alternatives. Initial model versions may begin as simple conceptual influence diagrams and then become more mathematically explicit as information is gained or assumptions are explained. Mathematical models that capture host population dynamics and parasite transmission can also improve understanding of the epidemiological processes underlying observed infection patterns (Keeling and Rohani 2008). Published examples of such models range from system-specific models to more general theoretical models, and range in complexity from spatially implicit deterministic models to stochastic agent-based models (several examples are summarized in Appendix S1: Table S1).

In some cases, using multiple model structures or parameterizations to consider alternative hypotheses can aid in the estimation of effects of assumptions made during model development. For instance, Wilberg *et al.* (2008) used different parameterizations of a spatially explicit stochastic simulation model to evaluate source–sink population dynamics within a fishery. In systems where transmission biology is not well understood, exploring a suite of transmission rates can rule out transmission modes if model simulations indicate that a particular transmission route is unlikely to produce observed infection prevalence. Rates in these models can also be modified to represent the hypothesized effects of both management action and disease (Figure 2). Information gaps that lead to simplifying assumptions or difficulties in estimating model parameters are a challenge for using models to support management. Nonetheless, predicting the performance of management alternatives can occur even when disease dynamics within a managed system are imperfectly understood (Russell *et al.* 2017). A collaborative model-building effort may further help to foster a common understanding among participants and reveal otherwise hidden assumptions.

Assessing disease consequences and trade-offs

Potential decision outcomes (ie consequences) can be assessed using performance metrics associated with each measurable objective. A number of performance metrics, often based on fishery catch or effort, have been applied including average catch, catch variability, and bycatch (Bordalo-Machado 2006; Punt 2017). We anticipate that several performance metrics might be of interest for disease management. Notably, the expected probabilities associated with disease introduction or outbreak are likely to be informative when evaluating potential policy performance. Likewise, the anticipated amount of time a fishery is inaccessible or performing poorly due to disease could be compared to other performance metrics. Decision makers may also benefit from awareness of potential technical challenges to implementation, associated expenses, time to effectiveness, or side effects of treatment.

Production of seafood often entails competing objectives; therefore, considering trade-offs is a critical step in the structured decision-making process. Trade-offs are often considered in pairwise fashion when comparing two potentially competing performance metrics (eg yield versus variability in yield); however, more complex trade-offs can be analyzed graphically. For example, slightly more complex illustrations, such as "kite" or "radar" diagrams, can facilitate the visualization of performance, and these visual assessments may benefit from dedicated communication efforts among managers, modelers, and stakeholders (Punt 2017; Feeney *et al.* 2019). Even when such trade-off analyses are well presented, uncertainties may be difficult to assess and the decision maker's risk tolerance may still be unknown.

Sources of uncertainty about disease

Uncertainty about infectious diseases can influence the decision-making process in multiple ways (Table 2). For instance, in harvest management, both observational and implementation uncertainty are common (Williams *et al.* 1996; Francis

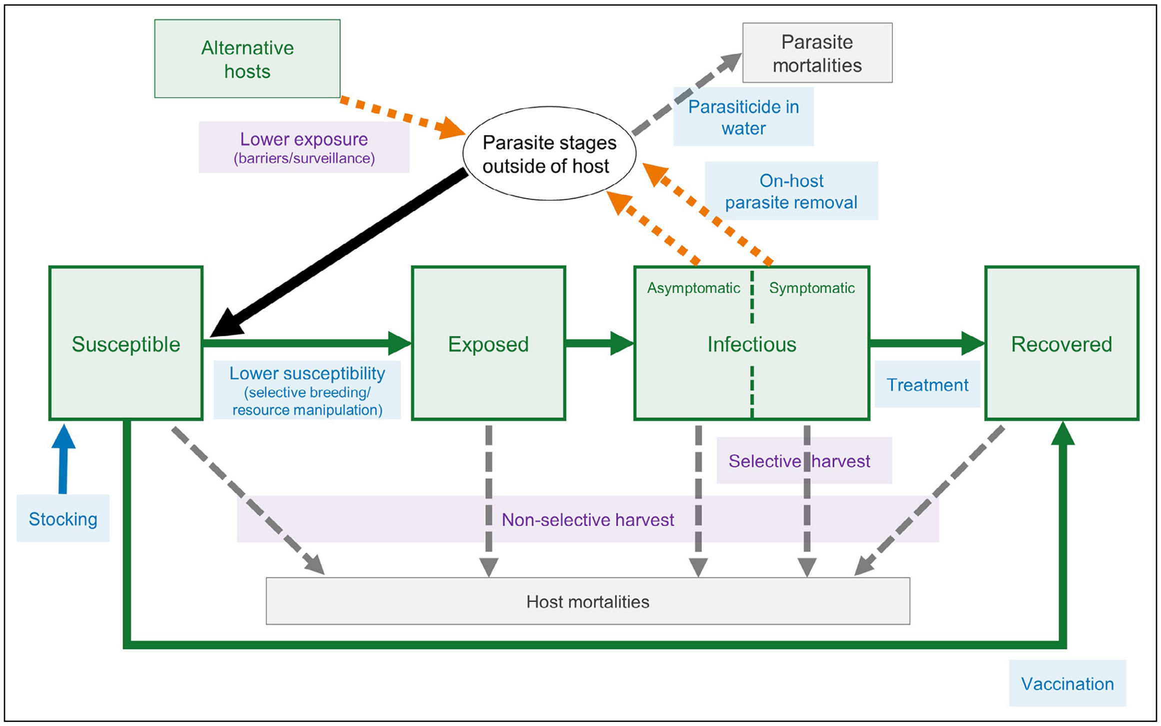

Figure 2. A generalized model of infection dynamics and the effects of potential management actions. The four central green rectangles represent the host stock by infection status: Susceptible, Exposed, Infectious (asymptomatic and symptomatic), and Recovered. The associated green arrows indicate transition rates between host infection status (infection, latency, recovery; for simplicity, loss of immunity is not shown). The fifth green rectangle represents alternative hosts that can also supply parasites to the system apart from the focal stock. Also shown as arrows: exposure to parasites (solid black), parasite shedding (dotted orange), mortalities (dashed gray) and stocking (blue). Blue and purple rectangles show potential management actions (blue for aquaculture or stocked fisheries, and purple for wild fisheries).

and Shotton 1997). Observational uncertainty (ie assessment uncertainty or partial observability) arises when the true status and trends of a target population deviate from what is being observed or reported. Such conditions may result from monitoring constraints (eg limited access to a population's inhabited area) or be intentionally introduced (eg deliberate misreporting of catches). Disease may increase observational uncertainty if the disease state is not accurately recognized or reported. For instance, if infected individuals alter behavior or activity rates, then their vulnerability to a sampling gear may change. Fishery decision processes could also be hampered by observational uncertainty if, for example, quotas are set based on the observed status of the harvestable stock (Deroba and Bence 2008). Along these

Table 2. Examples of uncertainties that may complicate an evaluation of anticipated performance of alternative actions taken to manage or mitigate disease for safe and sustainable seafood

Type of uncertainty	General description	Disease-management example	Operationalize
Process	Unknown structure and function of the managed system	What are the spatial processes for dispersal and transmission of pathogens?	Build multiple model structures to represent alternative hypotheses and adjust influence of these models as they gain or lose empirical support
Parameter	Unknown parameterizations for key model components	Are different sources of mortality compensatory or additive?	Identify plausible parameter values for scenario forecasting and refine as new data become available
Observational	Unknown relationships between samples and populations	Do infected individuals have different vulnerability to sampling gear?	Represent population assessment in scenario-forecasting models; intensify sampling
Implementation	Unknown effectiveness of actions or regulations	What is the response to treatment (ie effectiveness)?	Monitor and report responses to management action
Decision	Unknown objective weights or risk tolerance of decision makers	What trade-offs are acceptable and whose risks were considered?	Identify decision makers; visualize trade-offs; conduct sensitivity analyses; value learning

same lines, implementation uncertainty (ie partial controllability) indicates that the true effect of a management regulation may deviate from the anticipated consequence. For example, uncertainty about the potential effectiveness of a treatment to reduce parasites could be modeled using a probability distribution to allow managers to see the consequences of a range of potential effectiveness values. A more complicated example could occur if infected individuals with visible disease were to have lower value at market (Lafferty *et al.* 2015), which could reduce interest in harvesting even if some annual allowable catch remained. Forecasting such responses to policy implementation would likely require more assumptions than a simpler scenario where a fixed portion of catch was assumed as harvested.

Emerging diseases may also introduce new forms of "process" uncertainty. Disease transmission modes, seasonality and rates, potential variation in individual susceptibility, and the long-term consequences of disease are all likely to be poorly understood, particularly at the onset of a new disease or when a naive population is first exposed. A changing climate also may influence socioecological systems through different influential factors, introducing new questions for disease management (Byers 2021). For instance, what are the consequences of increased spread of exotic species (which may introduce novel pathogens), warming temperatures (which may increase the amount of time over the course of a year that is suitable for disease transmission), or more frequent drought (which may increase host stress or density)? Likewise, the potential for cross-contamination between aquaculture waters and surrounding waters (Lai *et al.* 2018) may remain an important source of uncertainty as land- or water-use practices change. In the Great Lakes of North America, fisheries management has recognized and targeted known uncertainties (eg about recruitment dynamics, trapping efficiency) to refine management options over time, by completing a cycle of adaptive management (Jones *et al.* 2015), which has demonstrated that management-relevant uncertainties can be reduced for large open-fishery systems. Reducing uncertainty would similarly be critical to developing an adaptive disease-management program.

Disease risk assessment

Like Thrush *et al.* (2011) and Irwin *et al.* (2016), we view "risk" as a combination of event severity and probability of occurrence. Aquatic fauna can have risks of stock depletion or extinction, which may be influenced by infectious diseases. In particular, the risks associated with expansion and intensification of aquaculture and a corresponding overlap with wild populations are notable. Diana (2009) listed eight negative effects of aquaculture on biodiversity; of these, one explicitly refers to disease ("Disease or parasite transfer from captive to wild stocks"), although others may connect more indirectly through density dependence, genetic diversity, or promotion of stressful conditions or antibiotic resistance. With respect to human health, risks are expected through harvesting, handling, or consuming seafood (FDA 2021).

Disease threats can influence the decision maker. Conceptually, a fishery manager may attempt to maintain an "acceptable" level of risk by increasing precautions to offset the increased uncertainty (Irwin and Conroy 2013) that may be introduced by an emerging disease. However, individual decision makers may vary in their tolerance for risk. At one end, a high tolerance for risk may lead to a willingness to accept an expected loss in pursuit of an outcome that has low probability and high reward (Irwin *et al.* 2016). Conversely, an intolerance for risk leads to a willingness to reject an expected benefit in an attempt to avoid possible outcomes that have low probability and high cost. Decision makers are likely to be particularly concerned with risks of infectious diseases that threaten human livelihoods by causing collapses in fisheries and aquaculture stocks upon which stakeholders depend (Mardones *et al.* 2011; Gambill *et al.* 2015).

Challenges to operationalizing disease management

While sharing an overarching objective to "provide safe and sustainable seafood", many fishery and aquaculture examples often vary with respect to available information and actions, including whether those actions target disease prevention, treatment, or mitigation. Thus, challenges remain for operationalizing disease management. Multiple uncertainties are likely to persist, particularly at the outbreak of a novel disease, when disruptions to the managed system, rates of infection and mortality, and effectiveness of available treatments may be even more difficult to anticipate. Such complexities have been observed in both wild systems and aquaculture systems, as well as when those systems are interconnected (see Appendix S1: Panels S1–S3 for selected case-study examples). Even successful treatments may eventually degrade if their effectiveness decreases over time (eg development of drug resistance; Kreitzman *et al.* 2018). Moreover, risks may vary in terms of short- and long-term benefits or costs. Grant *et al.* (2017) suggested that decision analysis be used to "improve strategies for countering emerging infectious disease". With a focus on a salamander pathogen, these authors identified four challenges to successful proactive conservation: (1) lack of overarching disease policy; (2) fragmented management responsibility and limited authority; (3) competing objectives; and (4) few effective, available options for control (Grant *et al.* 2017). We propose that many of these challenges also exist in the context of seafood supply, and that decision structuring and scenario forecasting can help overcome these challenges in support of disease management.

A proposed path forward for disease management

We conclude by reviewing steps and offering questions (sensu Irwin *et al.* 2016) to generate a proposed path forward for fishery disease management. However, these steps can also be useful for any manager confronted with the challenges associated with infectious disease.

Specify objectives (what do we hope to achieve?)

For the foreseeable future, "provide safe and sustainable seafood" is likely to remain a motivating objective. A more comprehensive list of subordinate objectives could be cataloged as decision makers increasingly focus on managing the threat of emerging disease for specific fisheries. Specific objectives, performance metrics, and reference points are likely to vary among fisheries, but broadly we expect that they are likely to connect to either the "rewards" of exploiting renewable resources or the "risks" associated with those activities.

Identify options (what can we do about it?)

To date, more options apparently are available for affecting disease transmission than for reducing the probability of death given exposure, particularly for wild fisheries. Given the vastness of some aquatic habitats, we expect that near-term available management alternatives will continue to target reducing disease transmission. In the future, options for maintaining or manipulating genetic diversity or age-structure of harvested populations may gain further attention. Challenges remain for determining how specific disease-management options, which thus far have often been imprecise instruments, can be implemented to optimize efficacy and efficiency.

Make predictions (what are the likely consequences?)

Capacity is being built to make predictions under different policy actions within decision-relevant time frames, while considering multiple uncertainties and multiple components of a managed system (eg both ecological and economic; Deroba *et al.* 2019). Forecasts are still needed to establish the potential trajectories of disease outbreaks and to evaluate the potential consequences of alternative management options. When applicable, incorporating disease-induced mortality may reduce the likelihood of overly optimistic predictions of potential harvests (Choisy and Rohani 2006).

Assess trade-offs (what are the justifiable losses and gains?)

In fisheries management, objectives for consumptive use may conflict with objectives for conservation (St Mary *et al.* 2000; Brown and Mumby 2014). Punt (2017) provided examples of how to visualize potential trade-offs in a management strategy evaluation. Inclusion of additional disease-related metrics in trade-off analyses can add important realism to fisheries decision analysis; however, these metrics may require increased cost and effort to produce.

Evaluate uncertainties (what are the risks?)

For disease management, important uncertainties are likely to be connected to probabilities of disease introduction, transmission, and consequences, as well as treatment effectiveness. By incorporating such uncertainties into scenario-forecasting models, managers, scientists, and stakeholders may be better able to co-evaluate the sensitivity of projected performance metrics to assumptions made about disease dynamics and if these change the relative decision influence of previously recognized uncertainties.

Identify and fill data gaps (what information is needed?)

Structured decisions help reveal what is known and what is unknown, and consequently which parts of a management process may be based on assumptions. Identifying how or when decisions are sensitive to assumptions could help direct question-driven monitoring programs to increase the quantity and quality of information available to decision makers. Likewise, monitoring plays a critical role in determining whether implemented policies have produced the intended effects.

Update information (what has been learned?)

Learning can occur through the adjustment of actions (eg adaptive management) and reduction of model uncertainty (eg which hypothesis about system structure has the most empirical support?). Responding to reduced parameter uncertainty (eg what is the expected disease transmission rate?) and implementation uncertainty (eg what is the expected efficacy of a disease treatment?) may rise in importance for adaptive disease management. We expect that a major learning opportunity for disease management will include a better understanding of what risks are considered to be acceptable and whether those risks are equitably distributed.

Conclusions

Infectious diseases can affect dynamics of harvested populations in ways that change yields and sustainability of stocks. Emerging diseases could make forecasting population dynamics and quantifying potential policy performance more difficult because more information is likely needed to accurately make those projections. Furthermore, there may be insufficient data on how a diseased population would respond to various management interventions. Thus, infectious diseases, and especially newly emerging ones, may complicate evaluations of management alternatives. If these challenges lead to selection of a suboptimal harvest policy, then sustainability of economic benefits may wane. Our recommendations for a structured decision-making approach should allow managers to more purposefully incorporate the influence of disease into planning and management efforts, and perhaps will help in the development of new methods or models that improve mitigation of the effects of disease.

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Data Availability Statement

No data were collected for this study.

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Medicine, University of Georgia, Athens, GA; [5]*Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA;* [6]*Shellfish Research Laboratory, Marine Extension and Georgia Sea Grant, Savannah, GA*