

Research Article

Evaluating risk of African longfin eel (*Anguilla mossambica*) aquaculture in Michigan, USA, using a Bayesian belief network of freshwater fish invasion

Katherine E. Wyman-Grothem^{1,*}, Nicholas Popoff², Michael Hoff¹ and Seth Herbst²¹U.S. Fish and Wildlife Service, Fisheries Program, 5600 American Blvd W, Suite 990, Bloomington, Minnesota, 55437 USA²Michigan Department of Natural Resources, Fisheries Division, P.O. Box 30446, Lansing, Michigan, 48909 USAAuthor e-mails: katherine_wyman-grothem@fws.gov (KEWG), nipopoff@gmail.com (NP), michaelhoff@comcast.net (MH), HerbstSI@michigan.gov (SH)

*Corresponding author

Received: 28 February 2018 / Accepted: 25 July 2018 / Published online: 14 September 2018

Handling editor: Mattias Johansson

Co-Editors' Note:

This study was contributed in relation to the 20th International Conference on Aquatic Invasive Species held in Fort Lauderdale, Florida, USA, October 22–26, 2017 (<http://www.icaais.org/html/previous20.html>). This conference has provided a venue for the exchange of information on various aspects of aquatic invasive species since its inception in 1990. The conference continues to provide an opportunity for dialog between academia, industry and environmental regulators.

Abstract

Global eel production through aquaculture has grown over 500% since the mid-twentieth century, with much of production occurring in East Asia. Recent proposal of *Anguilla mossambica* (Peters, 1852) (African longfin eel) aquaculture in the U.S. State of Michigan highlighted a need for greater understanding of potential risk posed by introducing this species to the United States and the Great Lakes region of North America. U.S. Fish and Wildlife Service rapid risk screening had previously characterized this species as posing “uncertain” risk to the contiguous United States. The aquaculture petition motivated a multi-expert risk assessment, an approach that promoted synthesis of published and unpublished knowledge on the poorly-studied *A. mossambica* along with tracking and quantification of uncertainty. A group of six scientists with expertise in eel biology, eel conservation, or fish health provided inputs to run the U.S. Fish and Wildlife Service’s Freshwater Fish Invasive Species Risk Assessment Model (FISRAM). As a Bayesian belief network, FISRAM required experts to estimate probabilities of harm to native species, ecosystems, and humans by a variety of mechanisms, as well as estimate probabilities of habitat suitability and transport. In their responses, experts emphasized lack of knowledge about many ecological interactions involving *A. mossambica*. However, they consistently rated its probability of transport high and expressed particular concern about concurrent introduction of the swimbladder nematode *Anguillicoloides papernai* (Moravec and Taraschewski, 1988) that parasitizes *A. mossambica*. Mean predicted probability that *A. mossambica* would be invasive, i.e., cause economic or environmental harm or harm to human health, was 0.24 when considering climate match to the Great Lakes basin only, and 0.57 when considering climate match to the contiguous United States. The range of predicted probabilities across experts was extreme. The State of Michigan has now used the results of this risk assessment to inform new pathogen testing and facility requirements in support of a recirculating aquaculture system (RAS) for *A. mossambica* in Michigan.

Key words: risk assessment, risk management, Great Lakes, decision support model, Bayesian network model, expert opinion**Introduction**

Aquaculture is a growing source of fish production globally, with its share of total production now approaching that of capture fisheries (FAO 2016).

Concurrent with the growth of this industry, aquaculture has increased in importance as a pathway for introduction of aquatic species outside their native ranges. At present, aquaculture is responsible for more international introductions of inland aquatic species than any other cause (Welcomme 1992; Lee

2010), and as more aquaculture facilities are built, resource managers are tasked with evaluating the risks posed by culturing and rearing non-native aquaculture species.

Freshwater eels are a valued species for aquaculture particularly in East Asia (Lee et al. 2003). The Food and Agriculture Organization of the United Nations' global aquaculture production dataset shows growth in eel aquaculture from 499 tonnes in 1950 to greater than 273,000 tonnes in 2015 (FAO 2017). Eels are farmed primarily for human consumption in fresh, smoked, or canned forms (Silfvergrip 2009), and carry a relatively high market price (Lee et al. 2003). Being catadromous, freshwater eels require marine conditions in which to spawn, so eel reproduction in aquaculture facilities is not easily attainable (Silfvergrip 2009). Eel aquaculture is maintained by continuous import of wild-caught individuals to the facility, typically at the juvenile or glass eel stage when eels migrate from oceanic spawning grounds into freshwater rivers (Welcomme 1992; Silfvergrip 2009).

In 2016, the U.S. State of Michigan received a petition from a company wishing to import *Anguilla mossambica* (Peters, 1852) (African longfin eel) at the glass eel stage for a recirculating aquaculture system (RAS) within Michigan. *A. mossambica* is native to the western Indian Ocean and is present in rivers from Kenya to South Africa as well as in Madagascar and other Indian Ocean islands (Castle 1984). The species has been imported to Japan, South China, and likely South Korea for aquaculture since the mid-2000s (Crook and Nakamura 2013; Lin et al. 2015), but it is not widely cultured compared to other eel species (Lee et al. 2003). The State of Michigan's concerns about granting this petition centered on the possibility of impacts to *Anguilla rostrata* (Lesueur, 1817) (American eel), listed as "endangered" on the IUCN Red List (Jacoby et al. 2014), and possible concurrent introduction of alien parasites and diseases. The only existing risk assessment for *A. mossambica* introduction to the United States was the U.S. Fish and Wildlife Service's Ecological Risk Screening Summary for the species (USFWS 2017). This rapid screening report concluded that the risk posed by *A. mossambica* to the contiguous United States was "uncertain" because of a lack of documented introductions or introduction attempts in natural habitats outside the species native range.

The State needed a more thorough risk assessment for *A. mossambica* to determine how to proceed on the aquaculture petition. State employees collaborated with U.S. Fish and Wildlife Service (USFWS) employees and a group of eel and fish health experts to conduct a risk assessment using a Bayesian belief network developed by the USFWS for freshwater

fish introduction (Marcot et al. 2018). Bayesian belief networks hold distinct advantages in their ability to use expert opinion to supplement empirical data and their transparent treatment of uncertainty (McCann et al. 2006). This project was the first to use the Freshwater Fish Invasive Species Risk Assessment Model (FISRAM) to inform a discrete management decision. Our modeling objectives were to estimate the probability of invasiveness of *A. mossambica* in the contiguous United States, with particular focus on inland lakes in the State of Michigan and the Great Lakes of North America, and to characterize uncertainty around the estimated probability of invasiveness as well as the model inputs.

Methods

Bayesian belief networks are networks consisting of nodes and directional linkages between nodes. Nodes can represent constants, variables, or functions, while linkages represent correlational or causal relationships. Underlying each node is a probability table that defines the probabilities for the possible states of the node; if the node has other nodes linked to it, the probabilities will be conditional on the states of those other nodes. Because of the directionality of linkages, some nodes will have no other nodes influencing them (these are referred to below as "input nodes"; see, for example, Habitat Disturbance in Figure 1), and one or more nodes will not influence others (these are referred to below as "output nodes"; Invasiveness in Figure 1). The probabilities associated with the input nodes are prior probabilities in the Bayesian sense, and the probabilities associated with the output node(s) are posterior probabilities in the Bayesian sense (McCann et al. 2006).

We used a previously-developed Bayesian belief network, the Freshwater Fish Invasive Species Risk Assessment Model (FISRAM, now the Freshwater Fish Injurious Species Risk Assessment Model; Figure 1; Marcot et al. 2018), to implement a multi-expert risk assessment for *A. mossambicus*. FISRAM was developed by subject experts in invasive freshwater fish characterization. During its development, the model was calibrated and tested using a case set of 25 known invasive and 25 known non-invasive freshwater fishes, for which the predictive accuracy of the model was 100%. The model was also peer-reviewed by five subject matter experts under U.S. Office of Management and Budget guidance for influential science. The peer review plan and reviewer comments are publicly available online (USFWS 2018).

FISRAM defines the term "invasive" as "a non-native species to a particular ecosystem whose

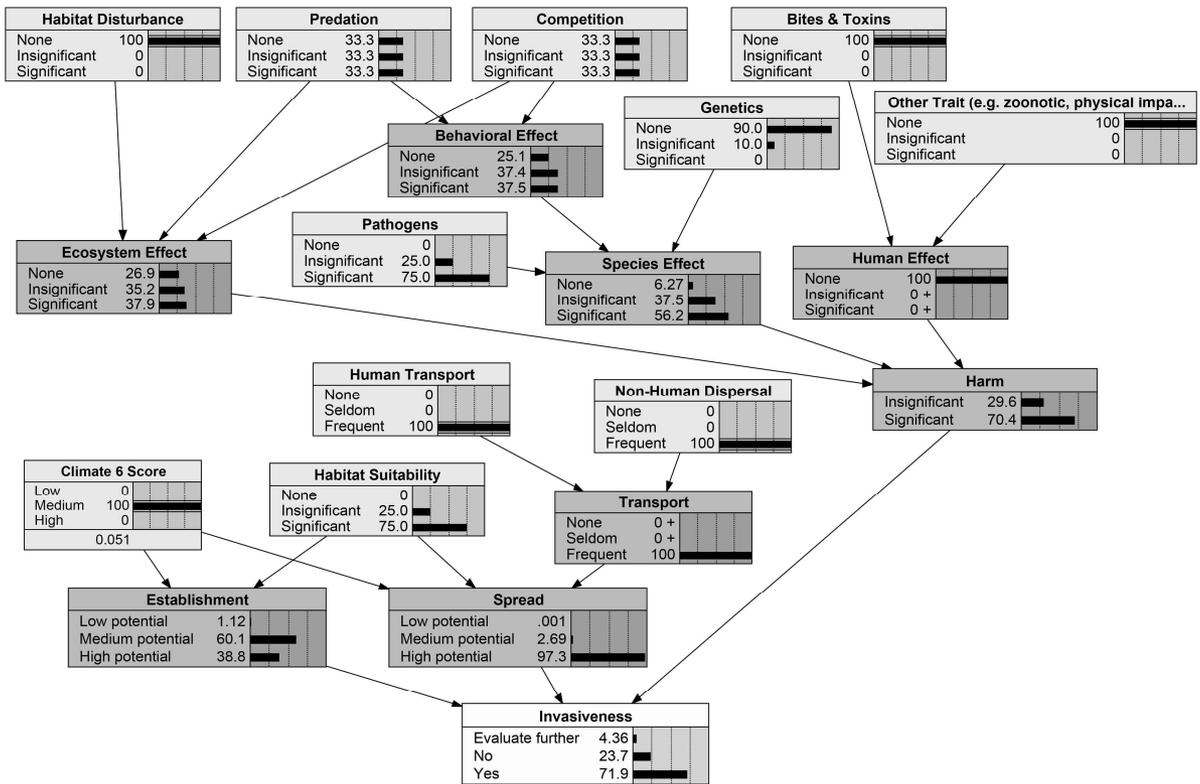


Figure 1. Structure of the Freshwater Fish Invasive Species Risk Assessment Model (FISRAM; Marcot et al. 2018), with example of African longfin eel (*Anguilla mossambica*) model output and inputs provided by an expert. Light gray nodes represent inputs, the white node represents model output, and arrows and dark gray nodes represent connections between input nodes and output nodes. Node states are listed below the node title. Bars indicate the probabilities assigned to the node states by the expert (input nodes) or the model (intermediate and output nodes).

introduction does or is likely to cause economic or environmental harm or harm to human health”, in accordance with Presidential Executive Order 13112 on Invasive Species. FISRAM is structured with seven input nodes representing discrete variables related to harm that could result from introduction (Habitat Disturbance, Predation, Competition, Bites & Toxins, Genetics, Pathogens, Other Trait). Additionally, FISRAM has four input nodes representing discrete variables related to transport, establishment, and spread (Human Transport, Non-Human Dispersal, Climate 6 Score, and Habitat Suitability). Each of these nodes has three states, representing a range of harm, transport, or establishment potential (Table 1). Implementation of the model requires that the input variables be quantified by individuals with expertise on the species or introduction in question. Only Climate 6 Score is not determined by expert opinion; it is a quantitative measure of the degree of similarity in climate between the species current established range and the target region for introduction, based on the work of Bomford et al. (2010).

We solicited participation for the present study from scientists based in North America, Europe, and Africa. All had served as the primary author on peer-reviewed publications on eel biology, eel conservation, or fish health. Six of these scientists (hereafter referred to as “experts”) agreed to participate. Expert participation was ample because three to five experts is a sufficient size to optimize returns on expert diversity (Clemen and Winkler 1999). We provided experts with the only known risk assessment for *A. mossambica* introduction to the United States (USFWS 2017), a FISRAM user guide, detailed definitions for the FISRAM input nodes and their states, a copy of the peer review conducted on FISRAM, and an example spreadsheet for another species to demonstrate how one might determine and justify the inputs. We then asked experts to provide probabilities for each state of each input node, references used to develop the probability distribution, and comments on how the probability distribution was developed. Experts completed their tasks independently of each other. Climate 6 Score was supplied by a prior climate

Table 1. Definitions and potential states of the ten variables that experts were asked to evaluate for *Anguilla mossambica*. These variables, along with a measure of climate match, formed the set of input nodes to the Bayesian belief network, FISRAM, that was used to assess risk posed by *A. mossambica* introduction. Experts were also given definitions of each of the individual states for each variable.

Variable	States	Definition
Habitat Disturbance	None, Insignificant, Significant	The capacity of the nonnative species to cause habitat modification (erosion, siltation, bank stability, eutrophication, sedimentation, etc.) thus causing destruction, degradation, alteration of nutrient pathways, trophic effects, etc. for affected species.
Predation	None, Insignificant, Significant	The capacity of the nonnative species to prey on affected native species, adversely affecting native populations.
Competition	None, Insignificant, Significant	The capacity of the nonnative species to adversely affect native species through competition for food, space, or habitat.
Genetics	None, Insignificant, Significant	The capacity of the nonnative species to adversely affect populations of the native species through direct genetic influences including hybridization, genetically modified organisms (GMOs), and introgression.
Pathogens	None, Insignificant, Significant	Epizootic; Infectious diseases are caused by pathogenic microorganisms such as bacteria, viruses, parasites, or fungi; these pathogens and parasites can be spread, directly or indirectly, from one animal to another. Includes pathogens that cause diseases listed by the World Organisation for Animal Health. [A pathogen is a bacterium, virus, or other microorganism that can cause disease. A disease is a condition of a living animal or plant body or one of its parts that impairs normal functioning.]
Bites & Toxins	None, Insignificant, Significant	Direct adverse effect on human health from bites, stings, or other injections, ingestion, skin contact, or absorption of venom from the nonnative species; or other consequences that lead to illness. Does not include effects from captive individuals; includes effects from wild and free-roaming individuals.
Other Trait	None, Insignificant, Significant	Pertains to species traits that could impart adverse effect on human health from other than bites and toxins that lead to illness, injury, paralysis, or death; or any other trait that characterizes any form of risk to humans.
Human Transport	None, Seldom, Frequent	Any assistance (whether intentional or unintentional) by humans for moving the subject species from one location to another and introducing the species into an environment beyond a range where it was established and can move from on its own.
Non-human Dispersal	None, Seldom, Frequent	Any assistance by non-human agents for moving the subject species from its current range beyond a range where it can move on its own.
Habitat Suitability	None, Insignificant, Significant	Habitat that matches the known habitats of the species, whether in the indigenous or invasive range of the species.

matching analysis that found a medium climate match to the contiguous United States for *A. mossambica* (USFWS 2017).

We entered and ran each expert's set of inputs individually through the FISRAM model in Netica (Version 5.24, Norsys Software Corporation). Netica uses the algorithms of Spiegelhalter et al. (1993), Jensen (1996), and Neapolitan (1990) to calculate posterior probabilities, i.e., the probability distribution for the discrete output states of Yes (the species is or will be invasive), No (the species is not or will not be invasive), and Evaluate Further. Because each expert's inputs were treated individually, we obtained six individual distributions of posterior probabilities. In the Results, we have presented the mean input and output probabilities for the group of experts as well as the range of individual inputs provided. For input nodes, we focus on probabilities for the highest state, i.e., "significant" or "frequent".

In May 2018, after completion of this study and application of the results, it became possible through a new version of our climate matching software (Sanders et al. 2018) to recalculate the Climate 6 Score as climate match to the Great Lakes basin only. We re-ran each expert's inputs as before, changing only the Climate 6 Score input.

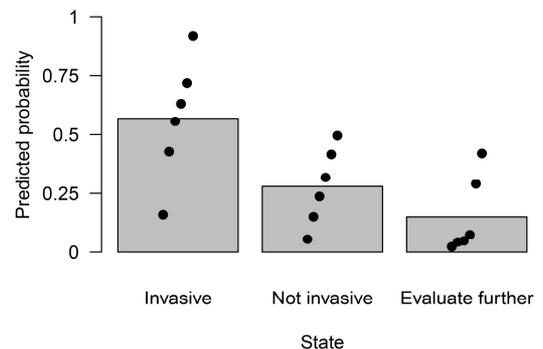


Figure 2. Predicted probabilities that the African longfin eel (*Anguilla mossambica*) will be invasive, not invasive, or will need further evaluation to predict invasiveness, obtained using a Bayesian belief network. Points represent six experts' independent model outputs. Shaded bar indicates mean predicted probability across all experts.

Results

Model Predictions of Invasiveness

The overall mean predicted probability that *A. mossambica* would be invasive was 0.57 (Figure 2). Across the individual runs of the model, the range of estimates was extreme (0.16–0.92). The mean predicted probability that the species would not be invasive

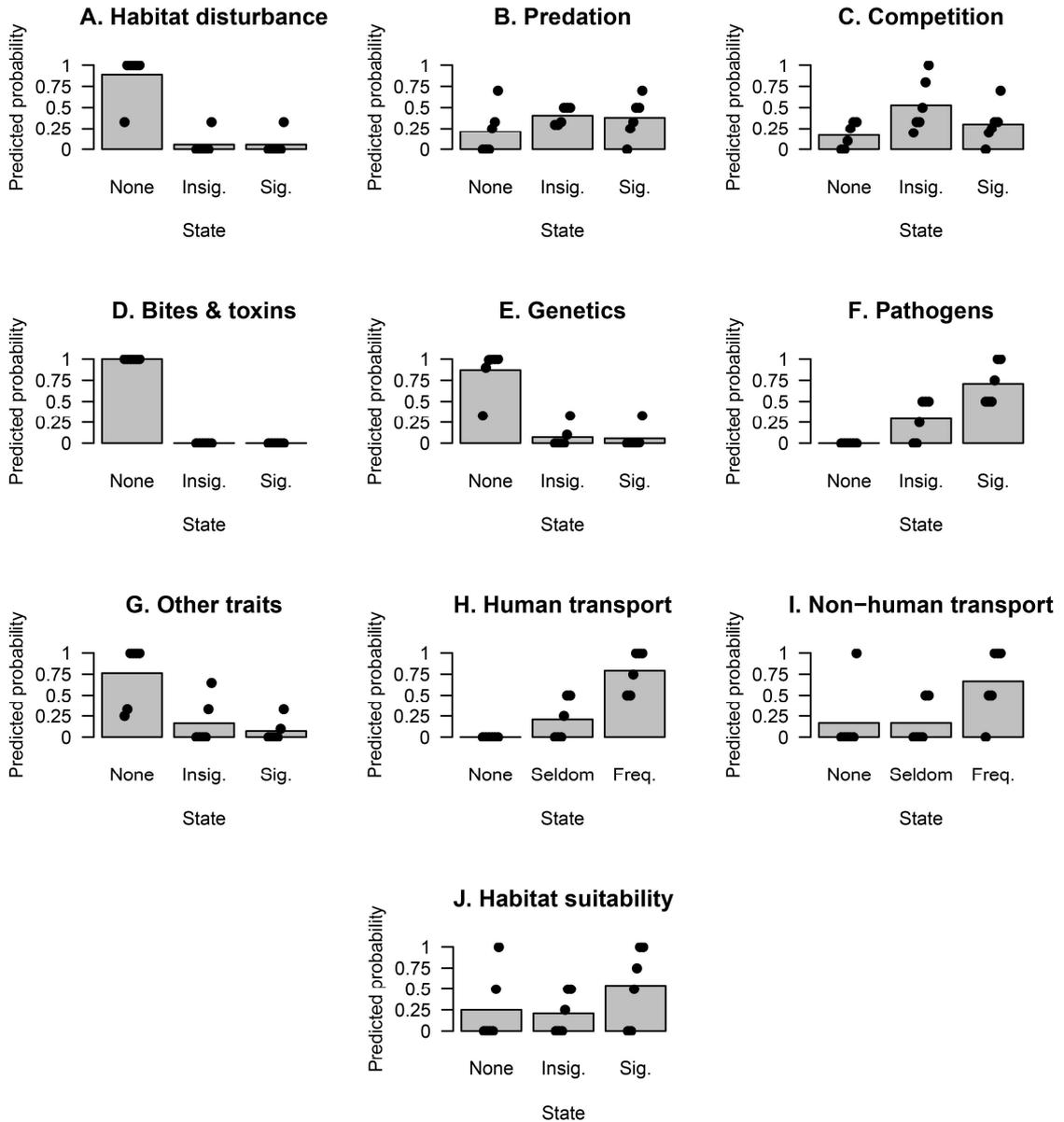


Figure 3. Predicted probabilities for each state of seven input variables indicating potential for harm (top and middle rows) and three input variables indicating potential for establishment and spread (bottom row) in a Bayesian belief network predicting invasiveness of African longfin eel (*Anguilla mossambica*) in the Great Lakes. Points represent six experts’ independent model inputs. Shaded bars indicate mean predicted probability across all experts. Abbreviations used in axis labels are as follows: “Insig.” = Insignificant; “Sig.” = Significant; “Freq.” = Frequent.

was 0.28, and the spread across runs of the model was less extreme (0.06–0.50). The inputs of two experts yielded relatively high probabilities for the state of “evaluate further” (0.42 and 0.29, respectively). In both cases, this result was influenced by a combination of lower estimates of significant habitat suitability and sensitivity of invasiveness to the potential for establishment.

Expert Responses: Potential for Harm

Experts considered concurrent introduction of pathogens to be the aspect of *A. mossambica* introduction most likely to result in “significant” harm (*mean probability* = 0.71; Figure 3F). Nearly all expressed concern about potential introduction of the parasitic swimbladder nematode *Anguillicola papernai* Moravec

and Tcharaschewsky, 1988 with *A. mossambica*. Other parasitic nematodes, an acanthocephalan parasite, a monogenean parasite, and flavobacteria to which *A. mossambica* is susceptible were also mentioned. Experts stressed that current knowledge on pathogens of *A. mossambica* is incomplete and numerous other pathogens may be of concern, including several with zoonotic potential.

In contrast, experts were unanimous that *A. mossambica* is harmless in the case of bites and toxins (*mean probability of “significant” harm* = 0.00; Figure 3D) and nearly unanimous that *A. mossambica* would have no effect via habitat disturbance (*mean probability of “significant” harm* = 0.06; Figure 3A) or via traits or mechanisms not explicit in the model (i.e., Other Trait, *mean probability of “significant” harm* = 0.09; Figure 3G).

On the subjects of predation, competition, and genetic effects, the experts expressed greater uncertainty (Figure 3B, 3C, 3E). All predicted some effect from predation on native organisms by *A. mossambica*, but not necessarily “significant” harm (*mean probability of “significant” harm* = 0.38). Similar predictions were made for the effect of competition of *A. mossambica* with native organisms (*mean probability of “significant” harm* = 0.30). A couple of experts highlighted cool temperatures and other barriers to population establishment in the Great Lakes as reasons for estimating “none” or “insignificant” harm from predation and competition. The difficulty of population establishment for this catadromous species was also cited as reasoning for a lack of “significant” genetic harm, such as through hybridization (*mean probability* = 0.06). However, half of the experts considered there to be at least a small possibility of hybridization with American eel.

Expert Responses: Potential for Establishment and Spread

Experts generally agreed on high probabilities for “frequent” human and non-human transport of *A. mossambica* (Figure 3H, 3I). Several pointed to the present study, motivated by aquacultural interest in the species, as clear evidence of “frequent” human transport (*mean probability of frequent transport* = 0.79). The migratory nature of eels, a history of eel escapes from aquaculture facilities, and tolerance of poor water quality were cited to support “frequent” non-human transport (*mean probability* = 0.67). Alternatively, one expert wrote that there was no evidence of non-human transport.

Expert opinions on habitat suitability were highly variable, reflected in a mean estimated probability of “significant” habitat suitability of just over 0.5 (*mean probability* = 0.54; Figure 3J). From the written explanations, this variability seemed to depend

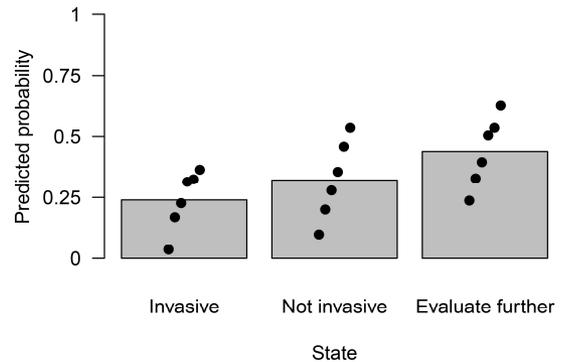


Figure 4. Predicted probabilities that the African longfin eel (*Anguilla mossambica*) will be invasive, not invasive, or will need further evaluation to predict invasiveness, assuming low climate match to the region of introduction: the North American Great Lakes basin. Predicted probabilities were obtained using a Bayesian belief network. Points represent six experts’ independent model outputs. Shaded bar indicates mean predicted probability across all experts. Models represented in Figure 2 and this figure differ only in the assumed climate match to the region of introduction.

primarily on whether experts considered habitat suitability over the full life cycle or not. Two experts stated that the species could occupy a wide range of habitats if escape occurred, while one expert focused on the catadromous life history and suggested that the marine habitat required for breeding would prevent *A. mossambica* establishment in the Great Lakes region.

Influence of Climate Match on Model Predictions of Invasiveness

When the climate matching analysis was updated to focus on the Great Lakes basin alone, the Climate 6 Score was classified as “low” instead of “medium”. The effect of this change was primarily to increase the probability of the state “evaluate further” (*mean predicted probability* = 0.44; Figure 4). Although the mean predicted probability that *A. mossambica* would be invasive (0.24) was 58% lower than before, the mean predicted probability that *A. mossambica* would not be invasive (0.32) only increased by 19%.

Discussion

Input from a variety of eel and fish health experts yielded a > 50% mean predicted probability of invasiveness for African longfin eel introduced to Michigan for aquaculture. The most consistent concern

among the experts was the potential for introduction of non-native pathogens. Experts disagreed most notably on establishment potential of African longfin eel in the Great Lakes region.

There are multiple precedents for the spread of eel parasites globally as a result of eel trade, including the spread of *Anguillicoloides crassus* (Kuwahara, Niimi and Itagaki 1974) Moravec and Taraschewski, 1988 from East Asia to Europe (Nagasawa et al. 1994) and North America (Hein et al. 2014); *Gyrodactylus anguillae* Ergens, 1960 from Europe to Asia, Australia, and North America (Hayward et al. 2001b); and *Pseudodactylogyrus anguillae* (Yin and Sproston, 1948) and *Pseudodactylogyrus bini* (Kikuchi, 1929) from East Asia to Europe, North America, and Africa (Hayward et al. 2001a). *A. mossambica* is the host of an endemic African swimbladder parasite, *Anguillicola papernai* (Moravec and Taraschewski, 1988), that is closely related to *A. crassus* (Laetsch et al. 2012). *A. crassus* infection can impair swimbladder function and reduce swimming speed, and it has contributed to mortality of farmed and wild *Anguilla anguilla* (Linnaeus, 1758) (European eel) in the presence of other stressors (Kirk 2003). The example of *A. crassus* infecting *A. anguilla* populations raises concerns over whether similar impacts could result from establishment of *A. papernai* in the United States with infection of native *A. rostrata*. Experimental infection of *A. anguilla* with *A. papernai* has shown that the parasite is not specialized to use only *A. mossambica* as a host (Taraschewski et al. 2005). Weyl et al. (2014) found *A. papernai* in adult African longfin eels sold with a veterinary certificate by a commercial supplier, raising concerns that the parasite could be transported undetected. The company petitioning in Michigan has maintained that imported glass eels are unlikely to be infected with *A. papernai* as they are caught prior to entering the freshwater systems where *A. papernai* is found. However, Kirk et al. (2000) demonstrate survival and infectivity of *A. crassus* in 100% sea water for several days, an ecologically significant period of time, and Nimeth et al. (2000) demonstrate that glass eels can become infected with *A. crassus*. Although *A. papernai* may not have the same habitat tolerances as *A. crassus*, until such tolerances have been tested, the studies on closely related *A. crassus* suggest a non-negligible risk of *A. papernai* introduction along with introduction of *A. mossambica* for aquaculture.

A weakness of using FISRAM to evaluate risk posed by a catadromous species is that it is designed for freshwater fish and does not explicitly accommodate anadromous and catadromous life histories. This issue likely contributed to the disagreement among experts over habitat suitability for African

longfin eel in the Great Lakes of North America. FISRAM's definition for habitat suitability is: "Habitat that matches the known habitats of the species, whether in the indigenous or invasive range of the species." This definition does not overtly encourage the expert to consider the possibility of different habitat requirements for different life history stages, despite referring to habitats in the plural. Some experts in the present study wrote about marine habitat requirements for reproduction and some focused on habitat requirements of the species at the stage and in the place where they could potentially be introduced. Thus, the breadth of the habitat suitability node definition may have added unnecessary uncertainty to the model results. We advise future users of FISRAM to clearly communicate any geographic or temporal boundaries of the analysis to experts to minimize such uncertainty, perhaps limiting the analysis to freshwater life stages given that FISRAM was developed and tested for freshwater fish only. However, establishment potential may not be particularly important for predicting impacts of hypothetical introduced *A. mossambica*. The maximum reported age for *A. mossambica* is 20 years (Froese and Pauly 2017), so with import of glass eels of less than a year of age (Réveillac et al. 2009), escapees could persist in the Great Lakes for nearly two decades without reproduction. Furthermore, the most consistent concern among the experts was the potential for introduction of non-native pathogens that could result without population establishment of *A. mossambica*.

We also evaluated the sensitivity of the predicted probability of invasiveness to climate suitability. The climate matching analysis for the contiguous United States estimated the climate suitability to be higher than the Great Lakes Basin-specific estimate. Changing the input Climate 6 Score from "medium" to "low" resulted in a lower predicted probability that *A. mossambica* would be invasive, as would be expected with a climate less suitable to establishment. There was also a tripling of the predicted probability that further evaluation was necessary. With so much uncertainty, a precautionary management approach (Sandin 1999) would suggest a similar management approach should be applied to both climate suitability scenarios. As with the question of habitat suitability, introduction of non-native parasites could occur even if *A. mossambica* could not establish due to climatic conditions in the Great Lakes basin. Evaluating the climate suitability of the Great Lakes basin for the parasites of *A. mossambicus* was beyond the scope of this study.

Studies based on expert knowledge or judgment may be seen as less reliable than studies based on empirical data (Sutherland and Burgman 2015). Experts can fall prey to various biases, such as

focusing on the evidence that is most convenient, overconfidence, and bias related to their own values or context (Morgan 2014; Sutherland and Burgman 2015). Our process took steps to mitigate some of these issues, including motivating the experts with recognition of their contributions including potential publication of findings, providing them each with the same set of background information and examples, asking the experts relatively narrow questions relative to the larger question of invasiveness, and selecting a diverse group of experts as opposed to a single expert or a homogenous group (Maguire 2004; Sutherland and Burgman 2015). At the same time, we were able to take advantage of important benefits of multi-expert risk assessment. First, information not available in the literature can be captured through expert consultation when time-sensitive decisions need to be made (Martin et al. 2011; Drescher et al. 2013). In the case of the poorly studied *A. mossambica*, experts were able to synthesize knowledge about the biology of other *Anguilla* species as well as knowledge about how *A. mossambica* compares to them to inform predictions about harm. The State of Michigan did not have the luxury of waiting for empirical studies to be carried out on these topics before deciding on the permit application. Second, expert opinion-driven risk assessment naturally lends itself to considering and quantifying uncertainty. Receiving inputs from multiple experts allows for tracking uncertainty through the risk assessment process (Vanderhoeven et al. 2017), as was done in the present study to contextualize the output of predicted probability of invasiveness. In some ways, the predicted probability of invasiveness was one of the less interesting results of the present study because the inputs and the uncertainty around the inputs pointed more directly to actions that could be taken to mitigate risks, such as more stringent pathogen management protocols.

Based upon the results of the present study, the State of Michigan developed specific pathogen testing and facility requirements for any RAS that would house *A. mossambica* in Michigan. These requirements include quarantines, facility siting outside of the 100 year flood stage and within a publicly owned sewage treatment plant, and effluent restrictions including ultraviolet disinfection, sludge pasteurization, and bio-security protocols. The information on pathogens supplied by experts participating in the risk assessment and their general agreement on this source of risk were critical in the decision to implement these requirements as opposed to others. The State of Michigan is now supportive of a RAS for *A. mossambica* in Michigan, as the risk assessment served as a valuable tool that enabled identification and mitigation of the clearest sources of risk.

Acknowledgements

The authors thank the eel and fish health experts who donated their knowledge and time to this study: B. Eltz, M. Gollock, K. Knopf, T. Loch, K. Phillips, and O. Weyl. The authors also thank M. Curtis, J. Goldberg, K. Holzer, A. Jersild, S. Jewell, B. Marcot, and C. Martin for their work in developing FISRAM. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service. Mention of commercial products does not necessarily imply endorsement by the U.S. government.

References

- Bomford M, Barry SC, Lawrence E (2010) Predicting establishment success for introduced freshwater fishes: a role for climate matching. *Biological Invasions* 12: 2559–2571, <https://doi.org/10.1007/s10530-009-9665-3>
- Castle PHJ (1984) Anguillidae. In: Daget J, Gosse JP, Thys van den Audenaerde DFE (eds), Check-list of the Freshwater Fishes of Africa (CLOFFA). ORSTOM, Paris and MRAC, Tervuren, Belgium, pp 34–37. Cited in: Froese R, Pauly D (eds), FishBase. <http://www.fishbase.se/summary/Anguilla-mossambica.html> (accessed 2 November 2017)
- Clemen RT, Winkler RL (1999) Combining probability distributions from experts in risk analysis. *Risk Analysis* 19: 187–203, <https://doi.org/10.1111/j.1539-6924.1999.tb00399.x>
- Crook V, Nakamura M (2013) Assessing supply chain and market impacts of a CITES listing on *Anguilla* species. *TRAFFIC Bulletin* 25: 24–30
- Drescher M, Perera AH, Johnson CJ, Buse LJ, Drew CA, Burgman MA (2013) Toward rigorous use of expert knowledge in ecological research. *Ecosphere* 4: 83, <https://doi.org/10.1890/ES12-00415.1>
- FAO (2016) Food and Agriculture Organization of the United Nations. The state of world fisheries and aquaculture 2016. Contributing to food security and nutrition for all. FAO, Rome, 204 pp
- FAO (2017) Food and Agriculture Organization of the United Nations Global aquaculture production 1950–2015 database. FAO, Rome. <http://www.fao.org/fishery/statistics/global-aquaculture-production/en> (accessed 2 November 2017)
- Froese R, Pauly D (2017) *Anguilla mossambica* (Peters, 1852). In: FishBase. <http://www.fishbase.se/summary/Anguilla-mossambica.html> (accessed 4 January 2018)
- Hayward CJ, Iwashita M, Crane JS, Ogawa K (2001a) First report of the invasive eel pest *Pseudodactylogyrus bini* in North America and in wild American eels. *Diseases of Aquatic Organisms* 44: 53–60, <https://doi.org/10.3354/dao044053>
- Hayward CJ, Iwashita M, Ogawa K, Ernst I (2001b) Global spread of the eel parasite *Gyrodactylus anguillae* (Monogenea). *Biological Invasions* 3: 417–424, <https://doi.org/10.1023/A:1015859109869>
- Hein JL, Arnott SA, Roumillat WA, Allen DM, de Buron I (2014) Invasive swimbladder parasite *Anguillicoloides crassus*: infection status 15 years after discovery in wild populations of American eel *Anguilla rostrata*. *Diseases of Aquatic Organisms* 107: 199–209, <https://doi.org/10.3354/dao02686>
- Jacoby D, Casselman J, DeLucia M, Hammerson GA, Gollock M (2014) *Anguilla rostrata*. In: The IUCN Red List of Threatened Species 2014: e.T191108A72965914, <https://doi.org/10.2305/IUCN.UK.2014-3.RLTS.T191108A72965914.en>
- Jensen FV (1996) An Introduction to Bayesian Networks. Springer-Verlag, New York, USA, 188 pp
- Kirk RS (2003) The impact of *Anguillicola crassus* on European eels. *Fisheries Management and Ecology* 10: 385–394, <https://doi.org/10.1111/j.1365-2400.2003.00355.x>
- Kirk RS, Kennedy CR, Lewis JW (2000) Effect of salinity on hatching, survival and infectivity of *Anguillicola crassus* (Nematoda: Dracunculioidea) larvae. *Diseases of Aquatic Organisms* 40: 211–218, <https://doi.org/10.3354/dao040211>

- Laetsch DR, Heitlinger EG, Taraschewski H, Nadler SA, Blaxter ML (2012) The phylogenetics of Anguillicolidae (Nematoda: Anguillicolioidea), swimbladder parasites of eels. *BMC Evolutionary Biology* 12: 60, <https://doi.org/10.1186/1471-2148-12-60>
- Lee CS (2010) Introduced species and aquaculture. *Bulletin of Fisheries Research Agency* 29: 69–78
- Lee WC, Chen YH, Lee YC, Chiu Liao I (2003) The competitiveness of the eel aquaculture in Taiwan, Japan, and China. *Aquaculture* 221: 115–124, [https://doi.org/10.1016/S0044-8486\(03\)00004-8](https://doi.org/10.1016/S0044-8486(03)00004-8)
- Lin Y, Gao Z, Zhan A (2015) Introduction and use of non-native species for aquaculture in China: status, risks and management solutions. *Reviews in Aquaculture* 7: 28–58, <https://doi.org/10.1111/raq.12052>
- Maguire LA (2004) What can decision analysis do for invasive species management? *Risk Analysis* 24: 859–868, <https://doi.org/10.1111/j.0272-4332.2004.00484.x>
- Marcot BG, Hoff MH, Martin CD, Jewell SD, Givens CE (2018) A decision advisory system for identifying potentially invasive and injurious freshwater fishes. *Unpublished manuscript*.
- Martin TG, Burgman MA, Fidler F, Kuhnert PM, Low-Choy S, McBride M, Mengersen K (2011) Eliciting expert knowledge in conservation science. *Conservation Biology* 26: 29–38, <https://doi.org/10.1111/j.1523-1739.2011.01806.x>
- McCann RK, Marcot BG, Ellis R (2006) Bayesian belief networks: applications in ecology and natural resource management. *Canadian Journal of Forest Research* 36: 3053–3062, <https://doi.org/10.1139/x06-238>
- Morgan MG (2014) Use (and abuse) of expert elicitation in support of decision making for public policy. *Proceedings of the National Academy of Sciences* 111: 7176–7184, <https://doi.org/10.1073/pnas.1319946111>
- Nagasawa K, Kim YG, Hirose H (1994) *Anguillicola crassus* and *A. globiceps* (Nematoda: Dracunculoidea) parasitic in the swimbladder of eels (*Anguilla japonica* and *A. anguilla*) in East Asia: a review. *Folia Parasitologica* 41: 127–137
- Neapolitan RE (1990) Probabilistic Reasoning in Expert Systems: Theory and Algorithms. John Wiley & Sons, New York, USA, 448 pp
- Nimeth K, Zwerger P, Würtz J, Salvenmoser W, Pelster B (2000) Infection of the glass-eel swimbladder with the nematode *Anguillicola crassus*. *Parasitology* 121: 75–83, <https://doi.org/10.1017/S003118209900606X>
- Réveillac É, Robinet T, Rabenevanana MW, Valade P, Feunteun É (2009) Clues to the location of the spawning area and larval migration characteristics of *Anguilla mossambica* as inferred from otolith microstructural analyses. *Journal of Fish Biology* 74: 1866–1877, <https://doi.org/10.1111/j.1095-8649.2009.02285.x>
- Sanders S, Castiglione C, Hoff M (2018) Risk Assessment Mapping Program: RAMP, version 3.1. U.S. Fish and Wildlife Service
- Sandin P (1999) Dimensions of the Precautionary Principle. *Human and Ecological Risk Assessment* 5: 889–907, <https://doi.org/10.1080/10807039991289185>
- Silfvergrip AMC (2009) CITES identification guide to the freshwater eels (Anguillidae) with focus on the European eel *Anguilla anguilla*, Version 1.1. The Swedish Environmental Protection Agency, Stockholm, 135 pp
- Spiegelhalter DJ, Dawid AP, Lauritzen SL, Cowell RG (1993) Bayesian analysis in expert systems. *Statistical Science* 8: 219–283, <https://doi.org/10.1214/ss/1177010888>
- Sutherland WJ, Burgman MA (2015) Use experts wisely. *Nature* 526: 317–318, <https://doi.org/10.1038/526317a>
- Taraschewski H, Boomker J, Knopf K, Moravec F (2005) *Anguillicola papernai* (Nematoda: Anguillicolidae) and other helminths parasitizing the African longfin eel *Anguilla mossambica*. *Diseases of Aquatic Organisms* 63: 185–195, <https://doi.org/10.3354/dao063185>
- USFWS (2017) U.S. Fish and Wildlife Service. African longfin eel (*Anguilla mossambica*) ecological risk screening summary. https://www.fws.gov/fisheries/ans/erss/uncertainrisk/Anguilla_mossambica_ERSS.pdf (accessed 2 November 2017)
- USFWS (2018) U.S. Fish and Wildlife Service. Invasive species prevention supporting documents. https://www.fws.gov/fisheries/ans/erss_supporting_documents.html (accessed 31 May 2018)
- Vanderhoeven S, Branquart E, Casaer J, D'hondt B, Hulme PE, Shwartz A, Strubbe D, Turbé A, Verreycken H, Adriaens T (2017) Beyond protocols: improving the reliability of expert-based risk analysis underpinning invasive species policies. *Biological Invasions* 19: 2507–2517, <https://doi.org/10.1007/s10530-017-1434-0>
- Welcomme RL (1992) A history of international introductions of inland aquatic species. *ICES Marine Science Symposium* 194: 3–14
- Weyl OLF, Taraschewski H, Moravec F (2014) Are African longfin eel imports a potential pathway for parasite invasions? *Journal of Fish Diseases* 37: 843–845, <https://doi.org/10.1111/jfd.12173>