Research Article

A decision support system for identifying potentially invasive and injurious freshwater fishes

Bruce G. Marcot[1,*], Michael H. Hoff[2], Craig D. Martin[3], Susan D. Jewell[3] and Carrie E. Givens[3,4]

[1]*USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon, 97205, USA*

[2]*USDI Fish and Wildlife Service, Fisheries and Aquatic Resources Program, Midwest Region, Norman Pointe II, 5600 American Blvd. West, Suite 990, Bloomington, Minnesota 55437-1458, USA*
Current: 81922 State Highway 13, Washburn, WI 54891, USA

[3]*USDI Fish and Wildlife Service, Branch of Aquatic Invasive Species, MS: FAC, 5275 Leesburg Pike, Falls Church, VA 22041, USA*

[4]*U.S. Geological Survey, Michigan Water Science Center, 6520 Mercantile Way, Suite 5, Lansing, MI 48911, USA*

Author e-mails: *bmarcot@fs.fed.us (BM), michaelhhoff@comcast.net (MH), craig_martin@fws.gov (CM), susan_jewell@fws.gov (SJ), cgivens@usgs.gov (CG)*

*Corresponding author

Abstract

An increasing threat to U.S. waterways is the establishment and spread of invasive and injurious fishes. A species may be designated by the U.S. Fish and Wildlife Service (USFWS) as federally "injurious" under the Lacey Act (18 U.S.C. 42) either if that species causes harm (injury) without establishing and spreading (not invasive), or if that species causes harm after establishment and spread (invasive). Species designated as injurious are prohibited from being imported, which is a highly effective way of preventing invasions by nonnative species. We developed a decision-support, risk-assessment system to aid USFWS's prioritization of species for injuriousness. Our system is based on USFWS's evaluation criteria of a species' potential injuriousness and consists of a semi-quantitative, rapid-assessment procedure called the Ecological Risk Screening Summary (ERSS) and a quantitative probability network model called the Freshwater Fish Injurious Species Risk Assessment Model (FISRAM). ERSS provides information on a species' history of invasiveness elsewhere in the world, and on its biology and ecology, potential or known effects of introduction, global and domestic distribution, and climate associations, and provides conclusions on potential risk of invasiveness. FISRAM calculates expected probability of injuriousness as a function of species potential establishment, spread, and harm, based on probable effects on native species and ecosystems, suitability of climate and habitat in introduced areas, ease of dispersal and transport, and harm to humans. FISRAM is used to assess risk probability when ERSS categorizes invasion risk as uncertain. We calibrated and updated the probability structure of FISRAM using a data set of 50 species with known invasiveness outcomes. We demonstrate the use of these two models for risk assessment and decision-support in identifying and documenting species for potential risk management actions, such as listing wildlife as injurious under the Lacey Act.

Key words: invasive species, decision support model, Lacey Act, rapid screening, risk assessment, risk management

Introduction

An examination of first records of newly established nonnative species showed that the annual rate of that documentation has increased

worldwide during the last 200 years, with 37% of all first records reported most recently (1970–2014) (Seebens et al. 2017). For all taxonomic groups, that increase has not shown any sign of saturation, and most taxa even show increases in the rate of first records over time. Thus, the effectiveness of recent efforts to prevent establishment of additional nonnative species has been limited.

As invasive species increase globally in number, distribution, and potential adverse ecological impacts (Pyšek and Richardson 2010), the need is great for a means of rapidly determining and prioritizing species for management focus. In the United States, a major consideration is the screening of foreign species to determine their potential for invasiveness, particularly for establishment, spread, and harm, before the species is introduced. A key law authorizing this task is the Lacey Act.

The U.S. Congress gives the U.S. Department of the Interior two authorities under the Lacey Act to help the U.S. Fish and Wildlife Service (USFWS) manage and interdict invasive species pathways. One authority is assisting States to intercept illegal importation and interstate transport of wildlife species and plants taken or possessed in violation of State, Federal, Tribal, or foreign laws (16 U.S.C. 3372). The second authority is prohibiting the importation of injurious wildlife and their transport between the continental United States, the District of Columbia, Hawaii, the Commonwealth of Puerto Rico, and any possession of the United States (18 U.S.C. 42, as amended), which is a lesser-known but significant part of the Lacey Act. This paper focuses on the latter authority, which is for designating species as injurious wildlife, and describes models designed to inform decisions for evaluating species as injurious under the Lacey Act.

The original Lacey Act was passed in 1900 (Act of May 25, 1900, Ch. 553, 31 Stat. 187-189) and prohibited the importation of all wild mammals and birds, except under special permit from the United States Department of Agriculture. The U.S. Congress initially unconditionally prohibited importation of all fruit bats (Pteropodidae Gray, 1821), the Indian mongoose (*Herpestes auropunctatus* Hodgson, 1836), the European starling (*Sturnus vulgaris* Linnaeus, 1758), and the house sparrow (*Passer domesticus* Linnaeus, 1758). Later amendments transferred injurious wildlife listing authority to the Department of the Interior (1939), reversed the nearly-blanket prohibition on mammals and birds to a prohibition on a small number of species designated as injurious wildlife (1948; those species could not be imported with a permit), and expanded the taxa to include fishes, reptiles, amphibians, mollusks, and crustaceans (1960). The Department of Agriculture retained the authority to designate harmful plants, called noxious weeds. However, there is overlap between Department of Agriculture and Department of Interior regarding wildlife, whereby both can prohibit the importation of wildlife if necessary to prevent the spread of a pest or disease to livestock or poultry. The missions

of both departments and their agencies are different, and their priorities for regulations focus on those missions.

Currently, the injurious provisions of the Lacey Act classify injurious species as wildlife found through regulation or Congressional designation to be "injurious to the interests of human beings, agriculture, horticulture, forestry, wildlife, or wildlife resources of the United States." Species that may be designated as injurious are limited to wild mammals and wild birds (not domesticated), and any fishes, reptiles, amphibians, mollusks, and crustaceans. Species are usually listed as injurious because of their invasive traits. A species also may be listed for the direct harm it can cause without establishing and spreading in the wild, such as because it would be particularly venomous or carry pathogens that affect wildlife or wildlife resources of the United States. To date, 726 injurious species have been designated—some by Congress but most by USFWS. In this paper, a species is called injurious if it has been federally designated as such.

The current list of injurious species is found in the U.S. Code of Federal Regulations (50 C.F.R. sec. 16.11 to 16.15, 2018). Fishes currently listed under the Lacey Act include all 122 species of walking catfishes (Clariidae), all 44 species of snakeheads (Channidae), 9 species in Cyprinidae, 2 species in Percidae, and 1 each in Centropomidae, Odontobutidae, and Siluridae. Also, all 228 species of salmonids (Salmonidae) are listed due to their potential to carry specific, harmful fish pathogens. The current list also includes 95 species of mammals, 10 species of reptiles, 4 species of birds, 6 species of crustaceans, and 2 of mollusks; 201 species (in 20 genera) of amphibians that carry a specific harmful pathogen are also listed.

About 40 percent (297) of the species were listed as injurious because of their invasive risk (not solely from harm as hosts of pathogens). Most of the invasive-risk species were not yet present in the United States and are still not known to be present. For example, only 2 of the 122 species of the walking catfish family listed in 1970 were established in the United States at the time, and that appears to remain true. Another example is the snakehead family listed in 2002 when only 3 of the 44 species were established in the United States, and no more appear to have been established since then. A compelling case can be made that the Federal government's regulatory authority has prevented many high-risk injurious species from entering the United States and becoming established. However, the Lacey Act's injurious provision has sometimes been used after the species had already invaded the United States by the time the problem was brought to USFWS's attention. A contributing factor to this problem was that, until the last few decades, biologists lacked the scientific modeling for predicting a species' potential for becoming invasive and injurious and thus justifying a designation.

The current work was spurred by the need to rapidly and efficiently identify nonnative species that may become injurious, such as is being

done in the European Union (EU) by a Scientific Forum advising a committee of representatives of the EU Member States (Genovesi et al. 2015), and in the United Kingdom by Centre for Environment, Fisheries and Aquaculture Science advising the UK Government (Copp et al. 2005). Also needed is a procedure to suggest species for potential listing under the Lacey Act for prohibiting their importation into the United States. Specifically, this project entailed developing a screening and evaluation framework and tools for aiding decisions on listing species; as a start, we focus on identifying potentially invasive freshwater fishes, whether in trade or as hitchhikers. Although USFWS has authority to designate a variety of taxa as injurious wildlife under the Lacey Act, freshwater fishes were selected for initial model development because of existing expertise within USFWS' Fish and Aquatic Conservation Program and because funding was provided for risk assessment on aquatic species through the Great Lakes Restoration Initiative. Our framework and tools do not replace USFWS's current listing process but rather aid in providing information used in that evaluation.

The literature provides an array of terms and definitions on invasive species (Ricciardi and Cohen 2007). Federal agencies are guided by Presidential Executive Order 13112 (White House 1999), as updated by Executive Order 13751 (White House 2016), stating that "'invasive species' means, with regard to a particular ecosystem, a non-native organism whose introduction causes or is likely to cause economic or environmental harm, or harm to human, animal, or plant health." In the context of this paper, we consider a narrower definition of an invasive species as a nonnative organism that establishes, spreads, and causes harm (Lodge et al. 2006). Economics will be considered at a later stage for any species proposed for listing as injurious. In the current project, "injurious wildlife" is the same as the current injurious provisions of the Lacey Act described above.

USFWS developed a standard list of criteria (Box 1) for evaluating species for listing as injurious. A species may fit only one criterion that contributes to injuriousness and still be injurious. For example, an injurious species may potentially transfer pathogens without that host species establishing and spreading, thus not falling under Lodge et al.'s (2006) definition of invasive. Thus, under E.O. 13751, all injurious species are invasive because they cause harm, but under Lodge et al. (2006), not all injurious species are invasive.

Various approaches have been developed to evaluate management of invasive species after they are established (e.g., Buchadas et al. 2017; Baker and Bode 2016; Britton et al. 2011). We focused on evaluating the potential of invasiveness and injuriousness before a species is introduced. Some approaches for evaluating species pre-introduction include the following. Daehler et al. (2004) used a categorical system to assess invasive plants in Hawaii and Pacific Islands. Paini et al. (2010, 2011) used a neural network self-organizing map to predict the likelihood of establishment of fungal

Factors that contribute to injuriousness

A. Likelihood and magnitude of release or escape, including pathway(s):

B. Likelihood and magnitude of survival and establishment (with or without reproduction) if released or escaped, including "acceptable" thresholds):

C. Likelihood and magnitude of spread:

D. Likelihood and magnitude of adverse impacts on native wildlife, wildlife resources, ecosystem balance, including what native species other than ESA listed species are or are likely to be affected?
   a. Potential for hybridizing or inter-breeding
   b. Competition for food and habitats
   c. Potential to cause habitat degradation and/or destruction
   d. Predation of native wildlife
   e. Potential to transfer pathogens
   f. Additional adverse impacts on native wildlife, wildlife resources, and ecosystem balance.

E. Likelihood and magnitude of effect on:
   a. Threatened and Endangered species. Please provide number of species.
   b. Designated critical habitats of Threatened or Endangered species
   c. Candidate species

F. Likelihood that one or more species may be placed in danger of extinction or endangered within the foreseeable future as a result of introduction/establishment:

G. Likelihood and magnitude of ancillary wildlife resource damages due to control measures (including, but not limited to, damage from equipment/chemicals used, increased risk of reinvasion due to ineffective treatment, or disturbance caused by removal):

H. Likelihood and magnitude of impact on *(high/low ranking not required)*:
   a. Human beings
   b. Agriculture
   c. Horticulture
   d. Forestry

I. Additional considerations that contribute or are likely to contribute to injuriousness

pathogens. Pheloung et al. (1999) evaluated the potential of plants introduced to Australia and New Zealand to become "weedy," using information on the species from outside the area of introduction and evaluations by expert opinion. Van Klinken et al. (2015) used a spatially explicit Bayesian network model to predict the spread of an invasive plant in eastern Australia. Koop at al. (2011) developed a weed risk assessment model for the entire United States that uses two elements of risk, establishment/spread potential and impact potential to evaluate the invasive and weedy potential of a species. That tool, along with a secondary

tool, was projected by the authors to "significantly enhance the United States' timeliness and accuracy in regulating potential weeds."

A popular tool for screening nonnative freshwater fish is the Fish Invasiveness Scoring Kit (FISK; Copp et al. 2009; Copp 2013), which was based on the weed risk assessment tool of Pheloung et al. (1999). FISK uses a scoring system of species invasiveness to denote the level of risk, scaled low to very high, and has been shown to be a useful tool to judge potential invasiveness (Almeida et al. 2013; Lawson et al. 2013; Puntila et al. 2013; Vilizzi and Copp 2013). FISK was revised to include ecological characteristics connected to invasiveness and climate matching in a wider variety of environments, expanding its original venue of temperate European climate zones to include subtropical and tropical climates (Lawson et al. 2013). This revised tool, along with four other taxon-specific decision-support tools— focused respectively on amphibians (Amph-ISK), freshwater invertebrates (FI-ISK), marine fish (MFISK), and marine invertebrates MI-ISK)—were combined into AS-ISK, or the Aquatic Species Invasiveness Screening Kit, a decision-support tool that considers species' biographical and historical characteristics and corresponding biological and ecological interactions (Copp et al. 2016a). To expand applicability to EU Regulations on invasive alien species, AS-ISK also specifies introductory text detailing general species information and potential socio-economic and ecosystem effects in addition to questions focusing on how climate change predictions derived from current climate change models may influence the species risk of introduction and establishment, dispersal, and ecosystem effects. Final assessment for a target species is determined under AS-ISK based on user-defined, expert opinion responses to risk assessment and climate assessment questions and the ranking of the level of confidence of those opinions (low, medium, high, and very high) (Copp et al. 2016b).

Hayes and Barry (2008) summarized results of 49 studies that together tested the significance of 115 characteristics of the biology, ecology, and environment of seven biological groups: birds, finfishes, insects, mammals, plants, reptiles and amphibians, and shellfishes. They found that climate match, history of invasive impacts (history of invasiveness), and number of arriving and released individuals (propagule pressure) were the best predictors of species invasion. USFWS and partner organizations, especially U.S. states, attempt to control propagule pressure through regulatory risk management (injurious wildlife listing and state regulations), so propagule pressure is a human transfer criterion of invasion instead of a species-specific biological or ecological criterion that can predict invasion. Bomford et al. (2010) found that climate match explained the establishment of introduced freshwater fishes in 10 countries. Howeth et al. (2016) found that climate match predicted establishment of non-native fishes in the Great Lakes with 75–81% accuracy. Climate match has also been used to successfully explain

establishment of invasive mollusks in the EU (Patoka et al. 2017) and establishment of fish diseases in the U.K. (Thrush and Peeler 2013), although Ibáñez et al. (2014) found that climate can have contrasting influences on some plant and invertebrate species.

All of these, and other such approaches, generally address species establishment and perhaps spread, but none integrates the full array of factors pertaining to potential injuriousness of an introduced invasive species (Garcia-Berthou 2007) as required by USFWS, and many use expert opinion alone in their risk evaluations. Ricciardi and Cohen (2007) cautioned that the impact of an invasive species on native biota (injuriousness) cannot be predicted from its establishment and spread alone (invasiveness). Leung et al. (2012) reviewed over 300 publications on risk assessment of invasive species and determined that quantitative models generally measure just single risk components of transport, establishment, abundance, spread, and impact. For example, Gallardo and Aldridge (2013) evaluated priorities for managing invasive aquatic invertebrate and fish species based on establishment and spread. Kulhanek et al. (2011) used abundance as a proxy for projecting potential impact of an invasive fish.

Leung et al. (2012) suggested that risk assessments can be applied more widely in invasive species management and policy situations if all risk components can be evaluated. Here, we present USFWS' Ecological Risk Screening Summary (ERSS) process that includes many risk components for rapid screening of vertebrates, invertebrates, and plants (USFWS 2016b), and the Freshwater Fish Injurious Species Risk Assessment Model (FISRAM). The ERSS approach was developed to meet the direction by the National Invasive Species Council (2008) to "develop screening processes to evaluate invasiveness of terrestrial and aquatic nonnative wildlife (e.g., fish, mollusks, crustaceans, mammals, birds, reptiles and amphibians) moving in trade." FISRAM was developed because rapid screening may conclude that risk of a freshwater fish species is uncertain without additional inputs and analyses. These evaluation tools were explicitly coupled to integrate and account for knowledge and uncertainties of potential introduction, establishment, spread, and harm caused by nonnative freshwater fish species. The tools integrate empirical data, climate models, expert knowledge, and model validation and updating in a rigorous approach.

One shortcoming of FISK and AS-ISK is that neither does quantitative climate-matching. Therefore, results of their climate match analysis may be based on subjective evaluations by the risk assessors. That is at least in part why Puntila et al. (2013) and Tricarico et al. (2010) recommended that there is a need to calibrate such decision-support tools (FISK and any others) for the different areas where they are used. FISRAM draws the quantified climate match for the species undergoing risk assessment by using CLIMATCH (Australian Bureau of Rural Sciences 2010), RAMP (Risk
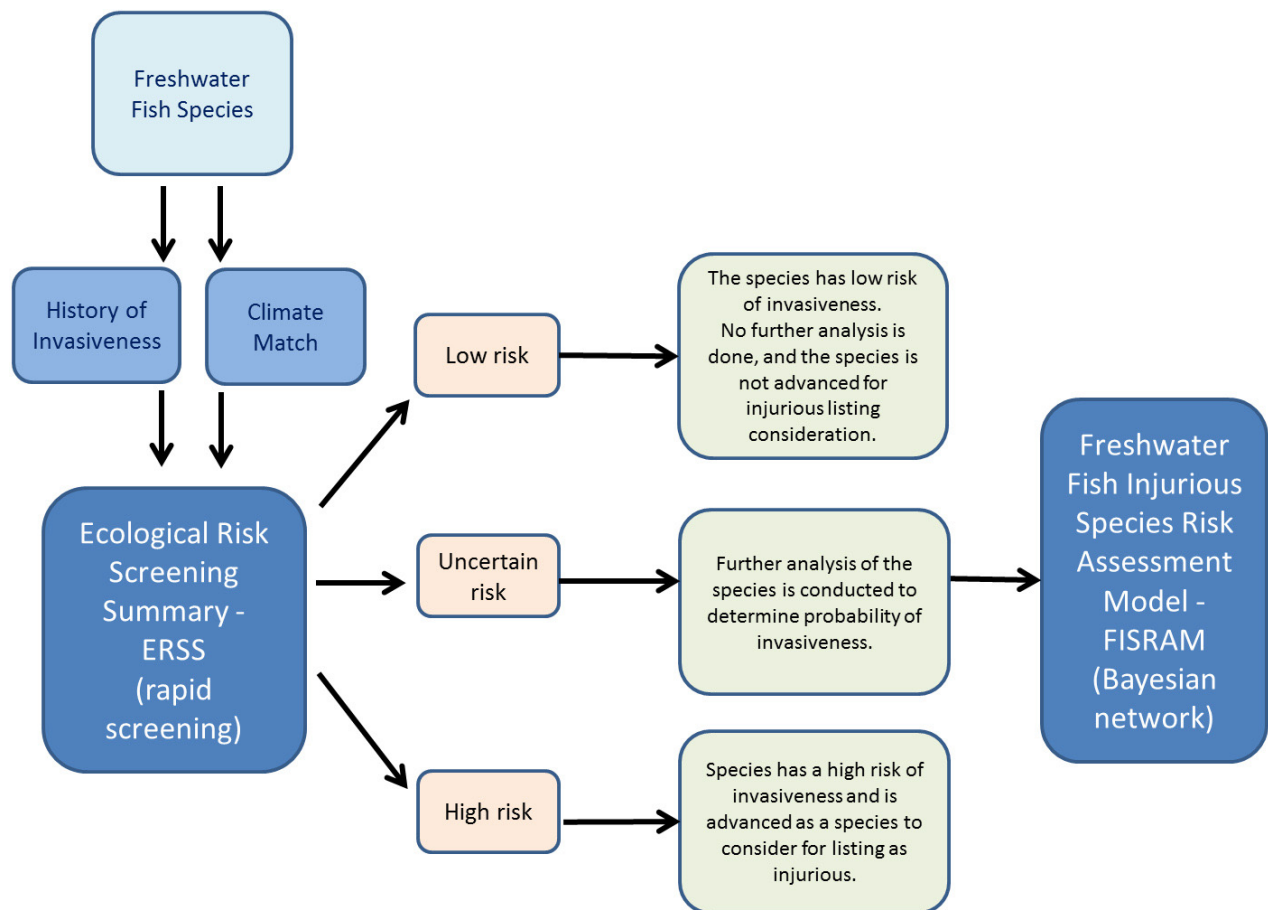
Figure 1. Components of the decision advisory system showing protocols to identify potentially invasive and injurious freshwater fish. Note that the ERSS species evaluation includes addressing, as pertinent to given species, native range, global distribution if found elsewhere, distribution in the United States, biology and ecology, documented impacts of introductions, climate match within the United States, assessment of risk, and uncertainty of the assessment.

Assessment and Mapping Program; Sanders et al. 2014), or both, which are peer-reviewed tools developed to objectively and quantitatively match climates for a species' current and projected ranges.

Materials and methods

Our tools for evaluating potentially invasive freshwater fish species are composed of two linked evaluation systems: (1) ERSS, a semi-quantitative, rapid-screening procedure (USFWS 2016b), and (2) FISRAM, a more quantitative, Bayesian network model. In brief, ERSS is used to determine the level of invasion risk for nonnative species, and, if the invasion risk is uncertain, then the species is further evaluated using FISRAM (Figure 1). ERSS also can be used to determine the risk of moving a native species from one ecosystem to another, and FISRAM can be used to help specify the cause and degree of certainty for a species already deemed by ERSS to be potentially invasive. The tools are complementary and were developed as follows.

Box 2. Categories and criteria used in the Ecological Risk Screening Summary (ERSS; see Figure 1) for evaluating ecological risk of invasive freshwater fish species in the United States (U.S.).

Overall assessment information
- Species common name, scientific name
- Author, month, year
- Species photograph

1. Native range and status in the U.S.
   - Native range
   - Status in the U.S.
   - Means of introductions in the U.S.
   - Remarks

2. Biology and ecology
   - Taxonomic hierarchy and taxonomic standing
   - Size, weight, and age range
   - Environment
   - Climate/range
   - Distribution outside the U.S. (native and introduced)
   - Means of introduction outside the U.S.
   - Short description
   - Biology
   - Human uses
   - Diseases
   - Threat to humans

3. Impacts of introductions

4. Global distribution

5. Distribution within the U.S.

6. Climate matching

7. Certainty of assessment

8. Risk assessment results
   - Summary of risk to the continental U.S.
   - Assessment elements
     - History of invasiveness
     - Climate match
     - Remarks/important additional information
     - Overall risk assessment category: Low, High, or Uncertain

9. References

10. References quoted but not accessed

Development, structure, and use of ERSS

ERSS is based on key factors that predict species invasion—history of invasiveness and climate match in the species' native range, as well as already-invaded range, if applicable. Other pertinent species information is also documented in an ERSS, including native range, global distribution if found elsewhere, distribution in the United States, biology and ecology, documented impacts of introductions, climate match within the United States, assessment of risk, and uncertainty of the assessment (Box 2; USFWS 2016b; for completed ERSS reports on a range of species, see: https://www.fws.gov/fisheries/ANS/species_erss_reports.html, which also

Table 1. Overall risk ranking outcomes in the Ecological Risk Screening Summary (ERSS) framework (USFWS 2016b).

Overall Risk Category		Climate Match		
		High	Medium	Low
History of Invasiveness	High	High	High	Uncertain
	Low	Uncertain	Uncertain	Low
	None Documented	Uncertain	Uncertain	Uncertain
	Uncertain	Uncertain	Uncertain	Uncertain

provides examples of the other pertinent species information previously mentioned). The information is interpreted in terms of individual risk elements (see Supplementary material Table S1) and then combined into a statement of overall risk (Table 1; USFWS 2016b).

ERSS works as a decision tree to determine if a species may be low, high, or uncertain risk (Figure 1), somewhat similar to the risk categories used by Pheloung et al. (1999), who used threshold values of scores determined from an empirical or training data set. Using ERSS entails the following process. First, the user ("ERSS author")—trained in the ERSS process as a risk assessor—compiles readily-available information derived from the recommended sources on species ecology, distribution, and invasion history, using international databases, scientific literature, and a peer-reviewed Australian model (Climate 6) that matches the climate of the species (via 16 climate variables) in its native and invasive ranges with similar climates in the United States (Australian Bureau of Rural Sciences 2010) or RAMP (Sanders et al. 2014) or both. The ERSS author documents the information accessed using checklists for quality assurance and quality control. The ERSS author uses the compiled information to determine the Overall Risk Assessment Category based on a matrix (USFWS 2016b).

The draft ERSS report is then reviewed by another biologist trained in risk assessment, to verify information, and then a final review is conducted by another biologist similarly trained. Any issues are discussed and resolved among the review team members. If the species is characterized as low risk, then it likely would not be considered for further action. If it is characterized as high risk, then the ERSS report may be presented to decision-makers and others for consideration of ameliorative management actions, such as listing the species as under the Lacey Act's injurious species designation. If it is characterized as uncertain risk, then the species may be evaluated further using the FISRAM model.

Development, structure, and use of FISRAM

Results of developing draft ERSS evaluations alone demonstrated the need to develop another tool to assess risk—FISRAM (https://abnms.org/bn/198). To date, USFWS has risk-assessed approximately 1,725 species using the ERSS process. Most of those species are categorized as uncertain risk, being candidates for using FISRAM to further assess probability of injuriousness. Examples of high, low, and uncertain risk fish species, resulting from the ERSS
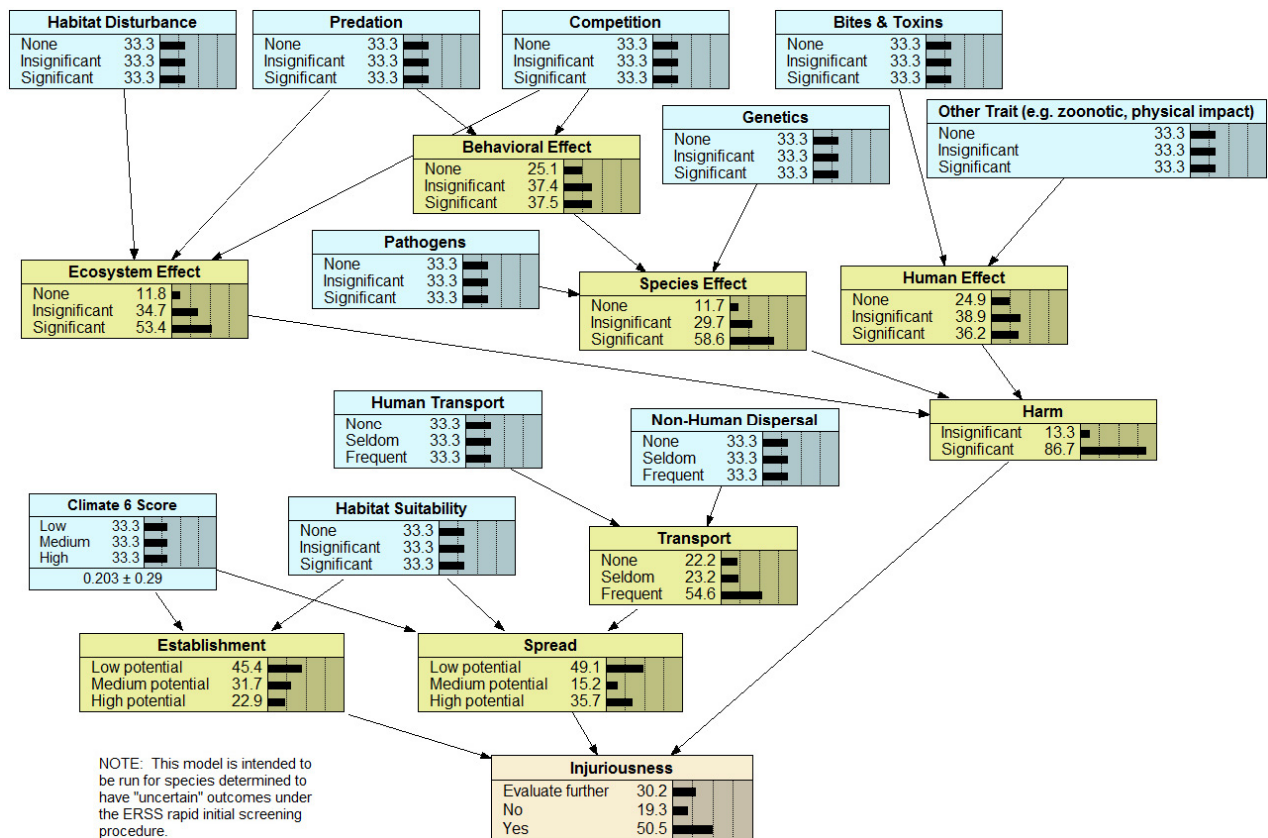
Figure 2. Bayesian Network Freshwater Fish Injurious Species Risk Assessment Model (FISRAM). The 11 input variables are the top-level "parentless" nodes (no other node feeds into them), shown here each parameterized with uniform prior probability distributions. Blue boxes denote input nodes, yellow boxes denote summary nodes, and the tan box denotes the final outcome node.

process, are available at USFWS 2015. Examples of freshwater fishes assessed as uncertain risk under ERSS are the brown hoplo (Callichthyidae: *Hoplosternum littorale* Hancock, 1828) and racer goby (Gobiidae: *Babka gymnotrachelus* Kessler, 1857).

FISRAM (Figure 2) is a Bayesian network that calculates the probability of the potential injuriousness and invasiveness of a species. A Bayesian network consists of a set of variables (nodes) linked with conditional probabilities representing logical or causal relations, and calculates outcome state categories with posterior probability distributions using Bayes' Theorem (Darwiche 2009; Fenton and Neil 2012). FISRAM evaluates variables pertaining to characteristics of a given species and calculates an overall probability that the species is injurious ("yes" outcome), is not injurious ("no" outcome), or when harm may be indicated when establishment and spread have low potential ("evaluate further" outcome). In FISRAM, the injurious state "evaluate further" is a dominant probability outcome when establishment and spread have low potential but harm is deemed significant. Such a situation can occur when a species is introduced that may not establish and spread, but could still cause harm. An example is an aggressive, venomous species imported and for which establishment and spread are unlikely if released; in this case, harm could come to handlers at incoming ports.

To develop the FISRAM network structure, we first reviewed policy, guidelines, mandates, and recommendations pertaining to identifying species invasiveness and injuriousness (ANSTF 1996; Lodge et al. 2006; NISC 2008). As a team of subject experts, we used this information to craft appropriate parameters and guide their linkages and conditional probabilities, using the software modeling package Netica (Norsys, Inc.), resulting in an initial "alpha" level Bayesian network model (sensu Marcot 2006).

We created the initial structure for the FISRAM model—how variables are defined and linked—based on a process using expert knowledge and experience of the authors and reviewers of the model in a structured expert-panel meeting conducted by the senior author. We based injuriousness on 11 input variables (all model nodes without incoming arrows; Figure 2) summarized into invasion dynamics of species establishment, spread, and harm (sensu Andersen et al. 2004; Rauschert and Shea 2017; Savage and Renton 2014). We parameterized the model as follows. We modeled the probability of species establishment as a function of the species' Climate 6 score (see above) and habitat suitability; spread as a function of habitat suitability and human transport or non-human dispersal; and harm as the effects of the modeled species on a combination of the ecosystem, potentially affected species, and humans. We structured ecosystem effect, in turn, as a function of habitat disturbance, predation, and competition; species effect as a function of predation, competition, and genetics; and human effect as a function of bites, toxins, and other species' traits potentially affecting humans. (see Table S2 for definitions of all variables and states in the model, including how the input variables are assessed for each species).

All but the 11 input variables in the model are parameterized by conditional probability tables representing the probability of various states given conditions determining them. Input variables are parameterized initially with uniform unconditional probabilities, which are adjusted based on knowledge of the species when running the model for specific cases.

We derived conditional probability values based on our group discussions, review of the literature, our own knowledge, and peer review (Table S3). Use of expert knowledge to build Bayesian models in ecology can provide robust tools when applied with rigor (Kuhnert et al. 2010) which, in the case of the FISRAM model, entails clearly explaining the basis of model structure and parameter values (Tables S3, S4) and especially seeking and incorporating peer review for models based mostly or solely on expert judgment.

In the initial model structure, without compelling ecological data or theory, we gave equal conditional probability weights to the "parent" input node variables that immediately link to the intermediate nodes (Figure 2), with the following exceptions. The Species Effect node is directly influenced by Behavioral Effects, Pathogens, and Genetics, with genetics given greater

weight because of potentially devastating and persistent effects on native species if they hybridize with invasive or injurious species. The Spread node is directly influenced by Transport, Climate 6 Score, and Habitat Suitability, with the potential for Spread mostly influenced by Habitat Suitability and Transport; without either of them, Spread has zero potential, whereas there still could be some potential for Spread when Climate 6 Score is low. And the outcome node, Injurious, integrates effects of Establishment, Spread, and Harm, with Harm having the greater influence because a species could be invasive even if Establishment and Spread have low potential, if there is some degree of Harm. For all these nodes, the weights used in their conditional probability tables vary by the specific different combinations of states of the parent nodes (see Table S3).

An advantage to the construction of FISRAM is that species that are harmful without being invasive can be assessed easily by using only the inputs to Harm, and determining the level of harm expected (in such an application, the other parts of the model are irrelevant and remain as uninformative priors). Examples are species that have the potential to seriously harm humans from bites or toxins, such as live, venomous species, even if they do not spread or establish in the wild.

Throughout the model development cycle, we used sensitivity analysis to determine if the model was structured as per expectations. Expectations were met if each node was appropriately sensitive to its immediate parent nodes and to the model inputs. We followed methods of sensitivity analysis in Marcot (2012), in which the degree to which the output node of the model (denoting the probability injuriousness) is influenced by incremental changes in each input node. Results, shown for each input node, are depicted as values of mutual information whereby higher values denote greater sensitivity (see Marcot 2012 for calculations).

Although knowledge-based tools can provide a robust evaluation system, also incorporating empirical evidence generally enhances predictive capability (Drolet et al. 2015). Thus, we tested and calibrated the initial FISRAM model component of the overall risk assessment framework against a case file (which was not used in the initial construction of the model) of 50 nonnative fish species with known outcomes (Table S5): 25 species that have all been documented as established outside native ranges and have been scientifically documented as causing harm (i.e., invasive) and presumed injurious, and 25 species that have all been extensively traded globally and the United States but have not been documented as invasive anywhere (not invasive) and presumed not injurious. The test cases were specifically chosen: with equal numbers of known conditions of invasiveness; that provided values on as many input parameters in the model as possible; that represent a variety of ecological conditions and species' attributes; with no prior knowledge of how they would specifically

perform within the model; and that might represent a potential range of conditions of establishment, spread, and harm so as to test model classification accuracy based on dominant probability states of being injurious or not injurious.

The model test entailed running all species through FISRAM and determining the proportion of species with correct predictions of injuriousness as the dominant outcome probability. Model calibration then entailed updating the existing conditional probabilities of the network by incorporating the case file using the machine-learning algorithm of expectation maximization (Dempster et al. 1977; Marcot 2012), a convergent log-likelihood function that incrementally improves the existing probability structure and the prediction performance of the model to best match the case file outcomes. We retained the initial probability values when running the algorithm, letting the results adjust values only where necessary, thus avoiding overfitting the adjusted model strictly to the 50-species case file. This calibration procedure served as much as an example of how the model can be incrementally tested and updated with new, known-outcome cases, as a means of fine-tuning the probability parameters in the model for initial release.

We then subjected the calibration-adjusted version of the model to individual reviews by five subject-matter experts (see Acknowledgments), following model review procedures of Marcot (2006) and Marcot et al. (2006), and per the Office of Management and Budget's peer review procedures for influential science (OMB 2004). We selected five reviewers to provide expertise collectively in freshwater and invasive species biology, population and community ecology, biodiversity, systematics, aquaculture, the pet industry, trade law, and risk analysis, and in general areas of conservation biology and environmental planning. Peer reviews addressed adequacy of the model structure including the parameters and their states, linkages, and unconditional (prior) and conditional probabilities. Peer reviews also provided advice and caveats on appropriate interpretation of model outcomes. We documented all peer review comments along with our reconciliation by amending the model according to key concerns and suggestions (www.fws.gov/science/pdf/Bayes-Net-Peer-Review-Plan-12-19-12-comments.pdf). This resulted in a refined "beta-level" version of the model, which is the final version presented here.

Peer reviews of the alpha version of FISRAM suggested, in part, exploring alternatives to the uniform distributions of the prior probabilities (33.3–33.3–33.3% among the three states in each input variable, as shown in Figure 2). The intent was to determine the influence of alternative prior probability distributions on overall model sensitivity and on predictions of injuriousness. Sensitivity was measured as mutual information, also called entropy reduction, which is calculated as the expected reduction in entropy (increase in information, measured in bits)

of an outcome variable given incremental changes in an input variable; higher values denote greater influence. It is well known, and at times a point of contention, that Bayesian analysis results (the calculated posterior probability distributions) can be sensitive to the values of the priors (Efron 2013). Although there was no empirical research or literature basis for suggesting specific alternatives for the FISRAM model, in consulting with the reviewers we explored two additional prior probability distributions for the input nodes: 50–25–25% and 45–45–10%. The rationale was that perhaps, in the absence of species-specific information on any input variable, either the least effectual states (appearing as "none" or "low" in the model) would be equally likely (50%) to the two, more effectual states (25–25%), or that the most effectual states ("significant", "frequent", or "high") would have lower probability of occurring (10%) than the other states (split 45–45%). We compared results of testing each of the model forms, with the three prior probability distributions, against the set of 50 fish species with known outcomes of injuriousness.

Further, to clarify, any default prior probability distributions (33–33–33, 50–25–25, or 45–45–10) in the Bayesian network model (FISRAM) would be applied in calculations of posterior probabilities in the model only when there was lack of knowledge and complete uncertainty on the values of any of the input variables; otherwise, particular values of the state probabilities in the input variables would be specified from whatever source is used, and those particular values then override the default prior distributions. This simply means that the prior probability distributions may affect outcomes, to whatever degree they would (as analyzed in our comparative sensitivity testing), only when there is total uncertainty about any input variable.

FISRAM is run by compiling information on a species of interest for as many of the input variables as may be available (Figure 2 and Table S1). Input variables can be set with probabilities distributed across one or more states depending on available information and uncertainty. One advantage of the Bayesian network modeling approach is that cases can be evaluated even with missing input data, for which the model reverts to using its prior uniform probability distributions for those variables, which would represent complete uncertainty for those variables. In this way, the model propagates and represents uncertainties in the final, calculated posterior probability distribution of injuriousness outcomes. The model can then be evaluated to determine the potential value of the missing information— that is, the degree to which model results may be influenced by setting the missing or highly uncertain input variables to extreme values. To this end, we ran the risk assessment framework on an additional six fish species of unknown injurious potential that were evaluated with ERSS and determined as "uncertain risk". Results were used to address the case of how uncertain-risk species may be addressed by decision-makers using their risk attitude in risk management.

Results

Use of FISRAM in species risk assessment

The alpha- and beta-level Bayesian networks both consisted of 20 nodes, 23 links, 33 unconditional (prior) probability values (in input nodes), and 459 conditional probability values (in all other nodes; see Table S2). To keep the model tractable and parsimonious, we kept all nodes categorical and consisting of only three states (except for the intermediate node "harm", which has only two states because there was no need to differentiate insignificant harm from no harm, under the Lacey Act applications; Figure 2).

From the results of testing the model with the cases of 50 fish species with known outcomes (Table S5), in every case, the model correctly predicted the dominant probability outcome of each species known to result as yes or no for Injurious. The known outcomes in the case file denoted only whether a species was injurious or not, which is why we used the dominant probability states as the test of model validation. Then, results of calibrating the model to the 50-species case file by using the expectation maximization algorithm resulted in only further fine-tuning the conditional probability structure of the model to include knowledge from the case file.

The updated model again accurately predicted all known species outcomes (Figure 3). The fine-tuning was evident in the slight improvement of dominant probability outcomes running the case file before (mean dominant probability outcome = 0.83, SD = 0.073) and after (mean = 0.88, SD = 0.080) updating. Examples of running the updated model on two cyprinid species resulting in a "yes" for injurious dominant probability outcome (black carp, *Mylopharyngodon piceus* Richardson, 1846) and a "no" outcome (silver barb, *Barbonymus gonionotus* Bleeker, 1850) are shown in Figures 4 and 5, respectively.

We found only minor differences in model sensitivity among the three prior probability distributions we tested (Figure 6). The rank order of sensitivity of the input variables (marked as "*" in Figure 6) was the same among all three distributions of the priors. The largest differences occurred with the intermediate variable "establishment" being the most sensitive under both the uniform prior distribution and the 50–25–25% prior distribution, and the intermediate variable "harm" being the most sensitive under the 45–45–10% prior distribution. These differences were not unexpected because of the different weighting of priors in the various arms of the model. With all priors set to their default values, that is, with no specification of any of the input variables, the resulting posterior probabilities of injuriousness among the three output states of "evaluate further", "no", and "yes" were [29, 44, 27%], [36, 34, 31%], and [30, 19, 51%], for the uniform, 50–25–25%, and 45–45–10% prior distributions, respectively. These outcomes, however, would be much more similar when specifying values of inputs on a given species. In a test of this, the three
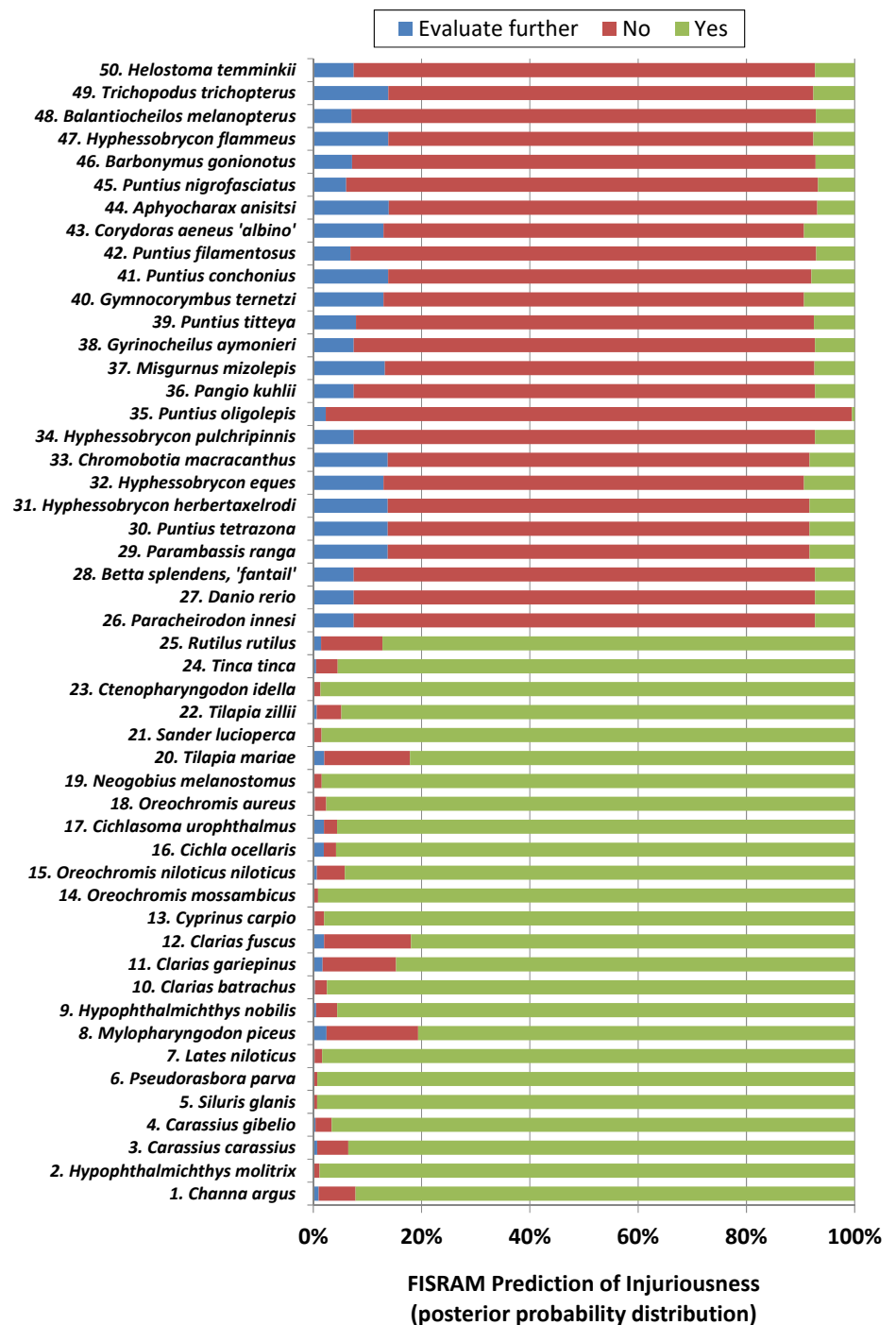
Figure 3. Results of running the beta-level FISRAM model with case file of 50 fish species with known invasiveness outcomes. Shown are the calculated posterior probability distributions of the three states of injuriousness in the model: evaluate further, no, and yes (see Fig. 2). Fish species are numbered as per the case file in Table S5 that also provides authorities. Species 1–25 are known to be invasive; species 26–50 are known to be not invasive. In every case, the model's dominant probability outcome among states correctly predicted the species' known invasiveness state.

variants of the prior probability distributions resulted in no differences in assessment of model accuracy when running the 50-species case file discussed above, because when running the cases, the probabilities of the input variable states get specified, essentially overriding their default prior distributions. Although it certainly can be advantageous to use expert knowledge to set
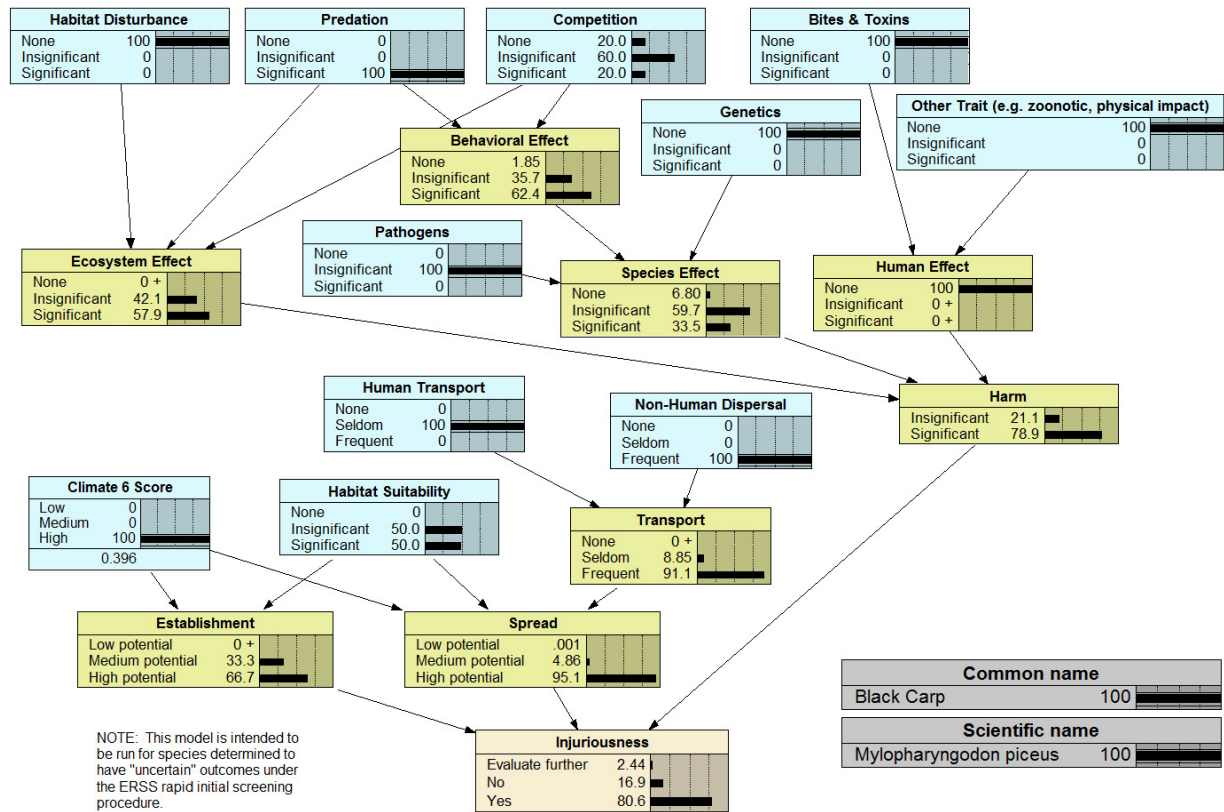
Figure 4. Example of running the beta-level FISRAM model on a species (black carp) resulting in a dominant probability outcome of "yes" (the species is injurious); this species is indeed known to be invasive and injurious. Input values (blue nodes) were specified by a review of the literature and expert knowledge (see species 8 in Figure 3 and Table S5).
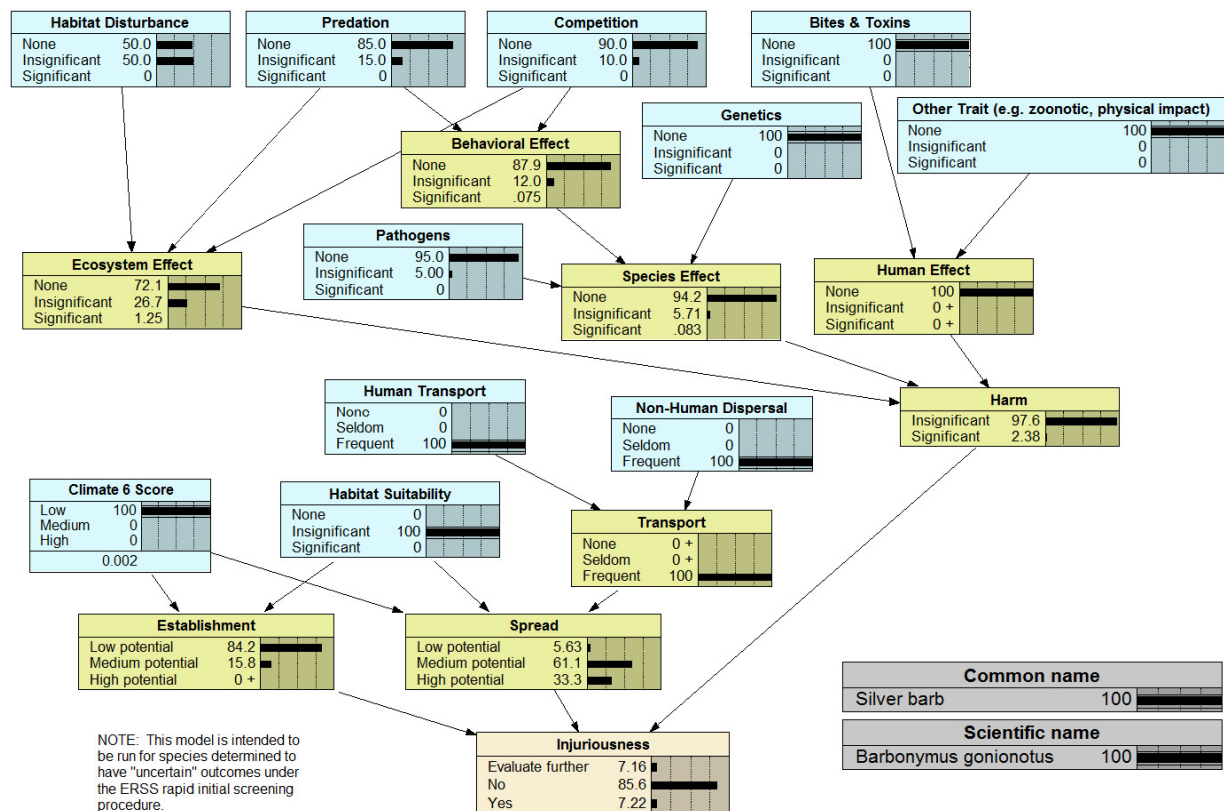

Figure 5. Example of running the beta-level FISRAM model on a species (silver barb) resulting in a dominant probability outcome of "no" (the species is not injurious); this species is indeed known to be not invasive or injurious. Input values (blue nodes) were specified by a review of the literature and expert knowledge (see species 46 in Figure 3 and Table S5).
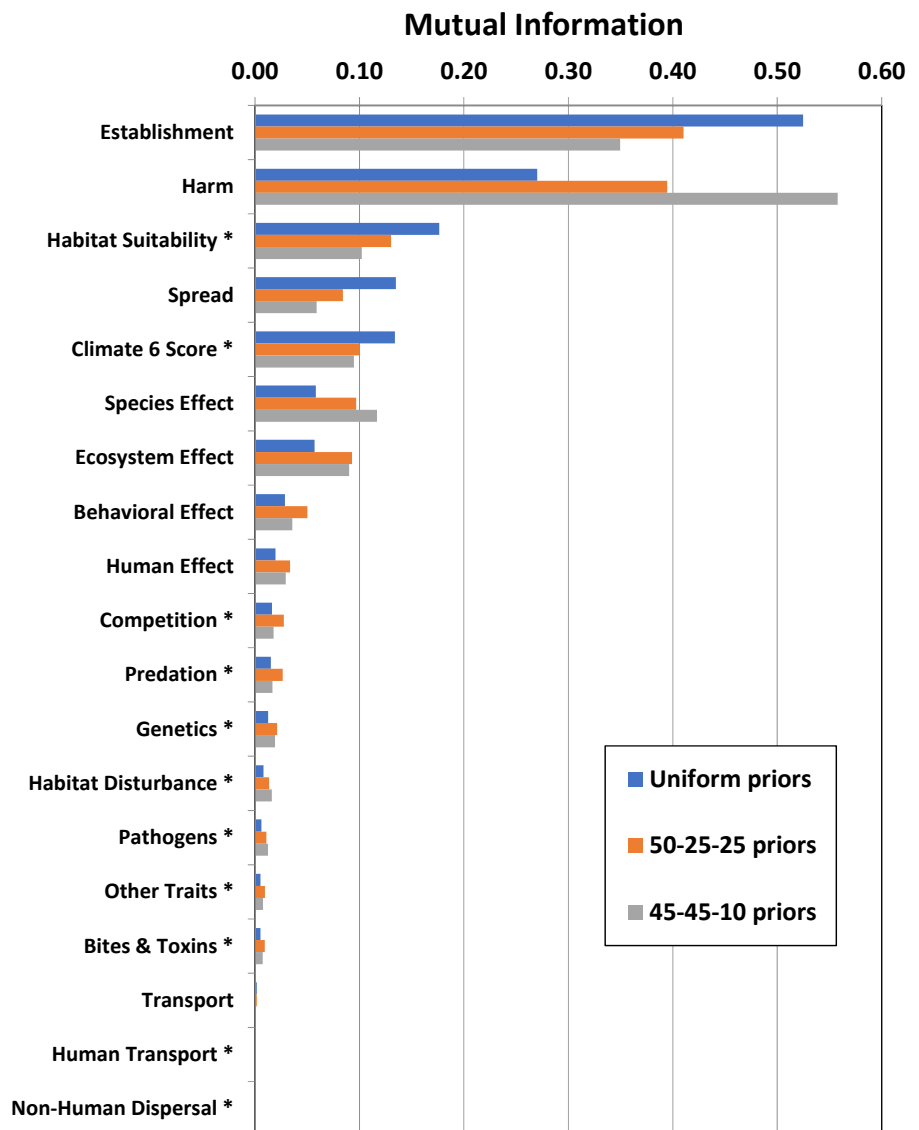
Mutual Information

Figure 6. Sensitivity analysis results of the freshwater fish injuriousness Bayesian network model using three distributions of prior probabilities. * = Input variables (parentless nodes in the model). Mutual information measures, in information bits, the degree to which the outcome of the model, injuriousness, is influenced by a particular variable; higher values denote greater influence, given the probability structure of the overall model. See Marcot 2012 for equation.

values of prior probabilities in some circumstances (Choy et al. 2009), we retained the uniform prior probabilities in the final model because of no overriding basis for deviating from that null distribution.

Examples of ERSS "uncertain risk" species further analyzed with FISRAM

We identified six example fish species that resulted in a determination of uncertain risk using the ERSS process. According to our protocol (Figure 1), we then further analyzed each species using the FISRAM network model to determine probability of injuriousness. FISRAM results were interpreted to mean that five of the six species may indeed be injurious and may warrant further management attention (Table 2). One species (Chinese fine-scaled loach, Cobitidae: *Misgurnus mizolepis* Günther, 1888) resulted in probabilities

Table 2. Examples of six fish species evaluated using the ERSS rapid risk screening procedure that resulted in a determination of uncertain risk and then further analyzed with the FISRAM Bayesian network model (see Figure 2) to determine probability of injuriousness.

Species	Basis of ERSS Determination	Probability of Injuriousness from the FISRAM Model[1]		
		FISRAM outcome = evaluate further	FISRAM outcome = no	FISRAM outcome = yes
Asian swamp eel *Monopterus albus* Zuiew, 1793	• Climate Match with continental U.S.: High • History of Invasiveness: Not scientifically documented	2	15	84
Chinese fine-scaled loach *Misgurnus mizolepis* Günther, 1888	• Climate Match with continental U.S.: High • History of Invasiveness: Not scientifically documented	8	54	37
Giant tigerfish *Hydrocynus goliath* Boulenger, 1898	• Climate Match with continental U.S.: Medium • History of Invasiveness: Not documented. There is no evidence this species was introduced and established outside its native range.	4	15	82
Oscar *Astronotus ocellatus* Agassiz in Spix and Agassiz, 1831	• Climate Match with the continental U.S.: High • History of Invasiveness: Not scientifically documented.	6	26	69
Barramundi *Lates calcarifer* Bloch, 1790	• Climate Match with the continental U.S.: High • History of Invasiveness: Not scientifically documented.	2	15	82
Red Piranha *Pygocentrus nattereri* Kner, 1858	• Climate Match with the continental U.S.: High • History of Invasiveness: Not scientifically documented.	2	11	87

[1] Values may not sum exactly to 100% because of rounding.

of 54% not being injurious and 37% being injurious (Table 2). Whether such probability values might still trigger management concern for this species would be the purview of decision-makers engaged in risk management who would assert their risk attitude on interpreting such outcomes in a broader context. To date, management decisions have not been made on these six species, and they are discussed here as examples.

Discussion

Use of risk assessment tools can help significantly to foretell and streamline management of invasive species outbreaks, such as used with forest insect pests (Withrow et al. 2015). Best targeted for evaluation with the coupled ERSS and FISRAM tools would be those freshwater fish species not yet imported into, or not yet established and invasive within, the United States. These tools can be used to identify species for which preventative measures could be appropriate. For example, the tools can contribute to evaluating and prioritizing species that USFWS could consider listing as injurious wildlife under title 18 of the Lacey Act, which would prohibit their importation.

Our approach fills the need for one risk assessment procedure that is not provided by other risk analysis methods, specifically in providing: (1) an initial, rapid-screening procedure (ERSS); (2) a standard template for documenting available information on species ecologies, distributions, and impacts; (3) a quantitative evaluation of climate match using existing, published climate-match tools; (4) explicit depiction and use of uncertainty in prompting a more quantitative risk evaluation (FISRAM); and (5) a repeatable quantification of risk probability outcomes rather than relying on subjective expert opinion. Further, the probability structure of FISRAM was developed using peer review and was cross-validated and tested against a suite of species with known attributes and outcomes of known invasiveness and injuriousness.

USFWS has completed hundreds of ERSSs, many of which had high-risk outcomes. Those high-risk species are currently the agency's priority for further review under the injurious wildlife evaluation criteria (Box 1). However, USFWS may also be petitioned by the public to list species. If a petitioned species results in an ERSS risk of uncertain, then the agency would run the species through FISRAM. If the outcome of FISRAM is "yes" for injuriousness, the agency may consider reviewing the species through the injurious wildlife evaluation criteria (Box 1); publish a proposed rule in the *Federal Register* seeking public comments; seek peer review of the assessment; address all required environmental, economic, and other determinations; and publish a final rule in the *Federal Register* that considers the elements from the proposed rule. A "no" FISRAM outcome would inform the agency that the species is not likely to be a priority for further evaluation and would be a low priority for expending the agency's limited resources. However, appropriate management action for a FISRAM outcome of "uncertain risk"—that is, with approximately equal probabilities of being injurious and being not injurious, such as with the additional six example fish species we used (Table 2)—would be determined by decision-makers' risk attitude in implementing policy. Also, FISRAM was designed so that it could be updated and fine-tuned as new, empirical data become available, such as by doing intermittent analyses of the biology, ecology, and effects of selected species that had been screened as injurious or not injurious. Further, the tools can be used not just as a decision aid, but also to help prioritize monitoring and research of species and conditions pertaining to injurious effects.

Particularly with the Bayesian approach, evaluations can still be made with some missing data (Parslow et al. 2013); for example, the network model would use the default prior probability distributions for any missing information on its input variables, and thereby propagate that uncertainty to the calculated outcomes of injurious probabilities. In this way, uncertainty itself becomes information of potential value to decision-makers whereby

the models can be used to determine the potential influence and value of additional information (e.g., Maxwell et al. 2015; Williams et al. 2011). This can be done by running "what if" scenarios setting unknown inputs to extreme values and determining if there are qualitative influences on the model outcomes. Still, due caution may be in order when information is unduly scarce on a species (McGeoch et al. 2012), whereby model outcomes may be more appropriately treated as initial, testable management hypotheses about injuriousness.

The species evaluation tools presented here thus are meant as decision-aiding devices, not final decisions. They offer a structured and repeatable approach to analyzing species (sensu Thomsen et al. 2011) but are not meant as demographic projection models or to quantify potential population sizes, rates of spread, and degrees and frequencies of potential harm. To achieve such estimates would take far more empirical study and data than will likely be available on most species to be evaluated. The tools are crafted based on determination factors under evaluation criteria developed for the injurious wildlife evaluations and are intended to be used by biologists, with results presented to decision-makers in USFWS. The tools also can be applied to broader contexts and modified to meet other screening and evaluation needs, such as for other taxa or other invasive species determinations. For example, USFWS is leading the development of a Bayesian network model version of FISRAM for use with crayfishes that are deemed as uncertain risk under ERSS. The FISRAM model also has recently been applied to evaluation of importation and injuriousness risk from African longfin eel (*Anguilla mossambica*) in a Michigan aquaculture in the Great Lakes region (Wyman-Grothem et al. 2018). Results are being used by the State of Michigan to guide policy on testing pathogens and requirements of aquaculture facilities.

Model evaluation results also may be made available to, and used by, other government agencies, industry venues, and the public. State governments may pass their own laws restricting invasive species, which they may do under a variety of situations that may not be appropriate for or authorized under Federal listing. For example, a state may be especially vulnerable to a particular invasive species that is not a threat to other states. State legislatures or conservation agencies could use this information to develop either proactive legislation or regulations to prevent trade of specific species within their jurisdiction, and live-animal importers could use the results to facilitate more responsible decision-making in their importation activities. For example, on January 10, 2015, the State of Michigan enacted Public Act 537 (State of Michigan 2015) with strong bipartisan support. This law established new protections to minimize the risk of invasive species in the State and stipulated that the State "shall use the risk assessment aquatic protocol developed by the USFWS", which has

used, and continues to use, ERSS, RAMP, and FISRAM. FISRAM could become an important component of Michigan's invasive species regulatory process. FISRAM is freely available through the USFWS authors. There is no specific species database for the model, as its purpose is to be used with new proposals for species introductions. There is, however, a database of 50 selected fish species, used to test and update (calibrate) the model (Supplementary material).

Decision-makers may apply different decision criteria when viewing probabilities of harm and injuriousness, for example with the probabilities of injuriousness of Chinese fine-scaled loach (Table 2). That is, they might view a particular percent probability of injuriousness as acceptable for one species but a different level for another species (or for the same species in a different location or circumstance), depending on the degree of uncertainty of the species' ecology, the type of and potential for injury by the species as known outside the United States, and other factors. That is, these tools are, appropriately, only part of a broader risk management framework and decision process. Similarly, when FISRAM results in an outcome of "evaluate further", such species would then be considered for potential management, listing, or other control measures under the purview of further evaluation by state or federal agencies whose mission includes reduction of harmful species risk.

There are broader implications of using these tools for various clients, stakeholders, customers who want to make responsible decisions for the pet trade, fish-stocking programs, and monitoring of invasive species for injurious effects. For example, in 2013 a memorandum of understanding (MOU) was established between USFWS, the Pet Industry Joint Advisory Council, and the Association of Fish and Wildlife Agencies on the development of nonregulatory approaches to reduce the risk of introducing potentially invasive species through international trade and to promote voluntary no-trade in certain species not presently in trade. USFWS's role within this MOU is to conduct risk assessments for species that are nominated by the states or industry. These results, in turn, can be used by the nongovernmental parties to: (1) promote awareness of species determined to be high or uncertain risk to the United States, (2) evaluate various voluntary mitigation practices that may be appropriate, (3) encourage their members to consider the environmental covenant pledge, and (4) provide nominations for species to be screened by USFWS. This example demonstrates how this work may be meeting critical needs of industry and other stakeholders.

Conclusions

The need is urgent for providing a decision support tool for identifying potentially invasive species (Andersen et al. 2004). We offer two evaluation tools to be used in tandem for determining the potential degree of

invasiveness of nonnative, freshwater fish species. Along with their respective user's guides (USFWS 2016b), the ERSS rapid risk assessment process and the FISRAM Bayesian network risk model can provide an efficient means of evaluating and screening many species for potential management consideration and listing as injurious. Evaluations of species can be fully documented through the use of these tools to provide a peer-reviewed, credible, transparent, and repeatable basis for advising risk management. Such documentation includes clearly denoting areas of knowledge uncertainty and its implications for projecting species' invasiveness status in the injurious listing evaluation and decision processes. We suggest a procedure of continuous improvement by testing and updating the models through the entire ERSS-FISRAM framework with new test cases. Using these tools provides value to help avert introductions of injurious or invasive species, even in the presence of uncertain knowledge and imperfect predictions.

Acknowledgements

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Supplementary material

The following supplementary material is available for this article:

Table S1. Risk ranking criteria of individual elements and overall outcome used in the Ecological Risk Screening Summary (ERSS) framework.

Table S2. Definitions of variables and states of the FISRAM freshwater fish injurious Bayesian network risk assessment model.

Table S3. Values of conditional probability tables (CPT) of the FISRAM freshwater fish injurious Bayesian network risk assessment model.

Table S4. Explanation of conditional probability values assigned in the FISRAM freshwater fish injurious Bayesian network risk assessment model.

Table S5. Case file of 50 freshwater species with known invasiveness outcomes.

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