Contributed Paper

Use of structured expert judgment to forecast invasions by bighead and silver carp in Lake Erie

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Abstract: *Identifying which nonindigenous species will become invasive and forecasting the damage they will cause is difficult and presents a significant problem for natural resource management. Often, the data or resources necessary for ecological risk assessment are incomplete or absent, leaving environmental decision makers ill equipped to effectively manage valuable natural resources. Structured expert judgment (SEJ) is a mathematical and performance-based method of eliciting, weighting, and aggregating expert judgments. In contrast to other methods of eliciting and aggregating expert judgments (where, for example, equal weights may be assigned to experts), SEJ weights each expert on the basis of his or her statistical accuracy and informativeness through performance measurement on a set of calibration variables. We used SEJ to forecast impacts of nonindigenous Asian carp (*Hypophthalmichthys *spp.) in Lake Erie, where it is believed not to be established. Experts quantified Asian carp biomass, production, and consumption and their impact on 4 fish species if Asian carp were to become established. According to experts, in Lake Erie Asian carp have the potential to achieve biomass levels that are similar to the sum of biomasses for several fishes that are harvested commercially or recreationally. However, the impact of Asian carp on the biomass of these fishes was estimated by experts to be small, relative to long term average biomasses, with little uncertainty. Impacts of Asian carp in tributaries and on recreational activities, water quality, or other species were not addressed. SEJ can be used to quantify key uncertainties of invasion biology and also provide a decision-support tool when the necessary information for natural resource management and policy is not available.*

Keywords: Asian carp, ecological forecasting, invasive species, Laurentian Great Lakes, risk assessment

El Uso de Juicio Experto Estructurado para Predecir Invasiones de Carpas Asiáticas en el Lago Erie

Resumen: *Identificar cuáles especies no-nativas se volverán invasoras y predecir el daño que causarán es complicado y presenta un problema significativo para el manejo de recursos naturales. Con frecuencia los datos o recursos necesarios para la evaluación de riesgo ecológico están incompletos o son inexistentes, lo que deja mal equipados a quienes toman las decisiones ambientales para manejar efectivamente recursos naturales valiosos. El juicio experto estructurado (JEE) es un método con bases matemáticas y de desempeño para obtener, sopesar y agregar juicios expertos. En contraste con otros métodos de obtención y agregación de juicios expertos (donde, por ejemplo, se le pueden asignar pesos iguales a los expertos), JEE sopesa a cada experto con base en su asertividad estadística y capacidad de informar por medio de la medida de desempeño*

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en un conjunto de variables de calibración. Usamos JEE para predecir los impactos de las carpas asiáticas no-nativas Hypophthalmichthys *spp. en el Lago Erie, donde se cree que no se ha establecido. Los expertos cuantificaron la biomasa, producción y consumo de la carpa asiática y su impacto sobre cuatro especies de peces si la carpa asiática se llegara a establecer en el lago. De acuerdo a los expertos, en el Lago Erie, la carpa asiática tiene el potencial de adquirir niveles de biomasa similares a la suma de biomasa de varios peces que se han cultivado comercialmente o recreativamente. Sin embargo, se estimó por los expertos que el impacto de la carpa asiática sobre la biomasa de estos peces sería pequeño, con poca incertidumbre. Los impactos de la carpa asiática sobre los tributarios y las actividades recreativas, la calidad del agua o sobre otras especies no se evaluaron. El JEE puede usarse para cuantificar incertidumbres clave de la biología de la invasión y también proporcionar una herramienta de apoyo para las decisiones cuando la información necesaria para el manejo de los recursos naturales y la política no está disponible.*

Palabras Clave: carpa asiática, especies invasoras, evaluación de riesgo, Grandes Lagos, predicción ecológica

Introduction

Globally, nonindigenous species introductions are increasing along with human populations, international trade, and transportation (Lockwood et al. 2013). A small proportion of these introductions lead to unwanted establishments with serious negative economic impacts, consequences for human health, and effects on biodiversity and ecosystem function (Williamson & Fitter 1996; Pimentel et al. 2005; Tatem et al. 2006). Determining which species can establish and cause harm in novel environments is of great scientific and practical interest.

Despite this interest, it remains difficult to predict which species will invade (Ricciardi et al. 2013). The science of forecasting biological invasions has benefitted from increased understanding of the dependence of population establishment and impacts on taxon-specific traits, environmental tolerances, propagule pressure, and population structure (Kolar & Lodge 2001; Lockwood et al. 2013). However, ecological forecasts of invasion outcomes remain uncertain due to the diversity and dynamics of species, receiving environments, and their interactions. Even when scientists are able to produce data or models that may provide necessary information, disagreement or differences of opinion may provide an additional obstacle to invasion forecasting and ultimately resource management and policy. As a result, most invasions are left unmanaged because resource managers and policy makers are ill equipped to determine and implement policies to prevent unwanted effects (Keller et al. 2009).

Those tasked with protecting natural resources often rely on expert knowledge for guidance in scenarios where data or models are inconclusive (Burgman 2005). A wide variety of approaches are used to obtain and combine expert judgments in applications ranging from nuclear regulation to food safety (Cooke 1991). Experts may be elicited individually and their judgments combined or a group consensus can be pursued. Group elicitation methods can include expert panels or use of the Delphi process (Helmer 1966) and its variants. These group approaches have been criticized due to bias resulting from dominant personalities or participants' desire to

achieve resolution (Kerr & Tindale 2011). Once expert judgments are obtained, they are often aggregated using weighted linear combinations of the experts' responses (see Clemen & Winkler 1999 for a review). In the simplest approach to expert aggregation, and one often used in conservation settings, equal weights are assigned to each expert and the aggregation becomes a simple arithmetic average. In other cases, weights may be assigned to experts by some subjective metric such as a ranking system based on experience or background or self-confidence assessments (Cooke 1991).

Here we applied structured expert judgment (SEJ) (Cooke 1991) as a performance-based (PB) method of weighting and aggregating expert judgments to address key uncertainties concerning biological invasion. With this method, each expert is elicited individually, and individual expert weights are obtained by measuring experts' performances. Expert performances are determined with empirical testing of individual abilities to provide informative uncertainty distributions on a set of calibration variable questions. SEJ has been used widely in nuclear regulation (Goossens & Harper 1998), civil aviation safety (Hale et al. 2009), public health (Tyshenko et al. 2010), sea-level rise (Bamber & Aspinall 2013), and ecosystem service applications (Rothlisberger et al. 2012). We applied it to the case of Asian carp invasion in the Great Lakes as a means to quantify uncertainty in a case in which scientific consensus is confounded by divergences of opinion and lack of data. The empirical information required to evaluate the potential outcomes of species introductions were either unavailable or not feasible or ethical to acquire at the appropriate time or spatial scales. We used SEJ so as to provide important information to enable timely management of biological invasions.

Problem Statement

We focused on the recent invasion of Asian carp (bighead carp [*Hypophthalmichthys nobilis*] and silver carp [*Hypophthalmichthys molitrix*]) in North America and on the potential ecological threat they pose to the

Laurentian Great Lakes, specifically to Lake Erie. In North American locations where they have become abundant, Asian carp have altered ecosystem structure and negatively affected commercial and recreational fisheries and human safety (Kolar et al. 2007). Concerns about Asian carp dispersal and establishment in the Great Lakes have been the source of ongoing litigation (State of Michigan vs USACE 2012), and over $150 million in U.S. federal funds have been spent to prevent its establishment in the Great Lakes. Hydrologic separation of the Great Lakes and Mississippi River basins has been proposed to prevent the passage of Asian carp and other non-native species between these basins (Rasmussen et al. 2011).

The introduction of Asian carp into Lake Erie, and all the Great Lakes, could come via contamination of bait, release by humans, and dispersal from established populations through Great Lakes waterway connections (Kolar et al. 2007). Federal agencies have identified the border of the Lake Erie watershed as 1 of 3 Asian carp high-risk pathways to the Great Lakes (United States Army Corps of Engineers 2010). Spawning bighead carp have been observed in connected rivers, and since 1995 3 bighead carp have been captured in western Lake Erie (Kocovsky et al. 2012). Bighead carp have been introduced to Lake Erie, but whether self-sustaining populations can exist and affect the ecosystem remains uncertain.

Methods

We used SEJ to elicit and combine expert judgments, with uncertainty, concerning the establishment of Asian carp in Lake Erie. Assessments by individual experts were obtained with 2–3 elicitors present. Each expert quantified his responses as percentiles of his (all respondents in this study were male) subjective probability distribution for each variable of interest, called a target variable. We aggregated expert assessments to form a combination termed a decision maker (DM) in 2 ways: each expert's assessment was given equal weight (EQ) or individual assessments were weighted according to their performance on a set of calibration variables (PB).

Calibration variables were from the experts' field of specialization, closely resembled the variables of interest, and had values that were not known to the experts at the time of elicitation, but these values were realized post hoc (Cooke et al. 1988; Cooke & Goossens 2000). For example, we asked experts to quantify the 2011 whole-lake biomass of yellow perch (*Perca flavescens*) in Lake Erie, a value measured annually by regional agencies and for which results were released in 2012, after the elicitations were conducted.

The number of calibration variables should be >10; however, the optimal number to use is unknown (Clemen 2008; Eggstaff et al. 2014). We used 20 calibration variables (Supporting Information) which included the

2011 Lake Erie estimates of biomass and stomach contents of walleye (*Sander vitreus*), yellow perch, gizzard shad (*Dorosoma cepedianum*), rainbow smelt (*Osmerus mordax*), smallmouth bass (*Micropterus dolomieu*), and white bass (*Morone chrysops*), as well as Asian carp harvest by commercial fishers in the Chicago Area Waterway. However, for 5 calibration variables, the actual values did not become available; thus, the number of calibration variables was 15. Expert 8 assessed only 11 calibration variables, further reducing the actual number of variables used for performance evaluation to 11. We assessed the robustness of DM performance to each calibration variable by comparing changes in the resulting DM caused by removing calibration variables one at a time.

PB weights were determined by calculating a calibration score and information score based on the calibration variables. The calibration score represented statistical accuracy and was the probability that the divergence between the expert's probabilities and the calibration variable realizations might have arisen by chance. For example, if an expert gave 90% confidence bands for the set of calibration variables, then it could be anticipated that about 10% of actual values would fall outside his or her chosen confidence bands. Thus, for an expert assessing 10 calibration variables for which realizations become known post hoc, 1 or 2 outcomes outside the 90% confidence bands are expected. However, if >5 of the 10 actual values fall outside the expert's bands, it is unlikely that so many outliers resulted by chance. Thus, the null hypothesis that the values of the calibration variables were independently sampled from a distribution complying with the expert's probabilities would be rejected. The higher the calibration score, the more accurately the expert assessed the calibration variable set.

The information score is the degree to which the expert's probability distribution is concentrated relative to the width of their expressed uncertainty band, and by the location of their median choice in relation to the calibration variable realization. Of these 2, statistical accuracy is more important, and informativeness was used to discriminate between statistically accurate assessments. The information score is relative to an analyst-selected background measure, which is defined by the smallest interval containing all assessments for a given variable (and the calibration variable realization if known). We calculated this information score for each expert on each variable and then averaged over all variables to obtain the overall information score for each expert. The product of an expert's calibration and information score determined the PB weight of his assessments. See Supporting Information for details concerning the calculation of performance measures and calibration.

The elicitation questionnaire (Supporting Information) consisted of 84 total variables, including the calibration variables. The portion of the questionnaire reported here was divided into 2 topical categories. The first category

included questions ($n = 14$) about the biomass, production (ratio of production to biomass [P/B]), and consumption (ratio of consumption to biomass [Q/B]) (Allen 1971; Palomares & Pauly 1998) at peak and at equilibrium conditions of bighead and silver carp in Lake Erie relative to the Lake Erie food web. These variables were elicited under the scenario that Asian carp successfully establish in Lake Erie. The second category included questions ($n = 8$) on equilibrium biomass in Lake Erie of high value species (walleye, yellow perch, gizzard shad, rainbow smelt) under 3 invasion scenarios: bighead carp establishment, silver carp establishment, and bighead and silver carp establishment. Associated rationales for the quantitative responses provided by experts for each variable were recorded. The questionnaire also included 2 other topical categories not reported here: predation on Asian carp by Lake Erie fishes ($n = 25$) and deterrence strategy efficacies for Asian carp ($n = 17$) (Wittmann et al. 2014).

For each variable, experts defined the 5th, 50th, and 95th percentiles of their subjective probability distribution. The following is an example of the question format:

If bighead carp were to establish in Lake Erie, what will its peak biomass be?

Units: metric tons per square kilometer, 1 metric ton = 1000 kg

5%_____ 50%_____ 95%_____

To select experts, we compiled a list of individuals with extensive knowledge as demonstrated through publication record and years of experience pertaining to the Lake Erie ecosystem or the ecology of Asian carp in North America or elsewhere. Based on recommendations from other Great Lakes scientists and on how many publications related to the elicitation topic an individual had authored, we invited 11 experts, all of whom agreed to participate (Table 1). The choice of the number of experts was supported by results of simulations that show that having >10 experts does not lead to increased performance of combined assessments (Meng 2005). Most SEJ studies use 5–10 experts; previous studies have used as few as 4 and as many as 50 experts (Aspinall 2006).

Prior to an in-person interview, each expert received the elicitation questionnaire, background information concerning expert elicitation, and a booklet containing biological information about the Great Lakes and Asian carp (available upon request). We interviewed each expert individually and in person from 1 May to 15 June 2012. Compensation was offered to all experts; some declined compensation. We assessed the robustness of the DM performance for each expert by comparing changes in DM that resulted from removing experts one at a time. All analyses were carried out with EXCAL-IBR (Cooke & Solomatine 1992) (freely available from http://risk2.ewi.tudelft.nl/).

Results

Performance and Combination of Expert Judgments

The experts' calibration scores were high and varied from 2×10^{-6} to 0.53. Nine of 11 experts scored above 0.05 (Table 2). To illustrate the variability in expert responses, Fig. 1 shows range graphs for a subset of representative calibration variable distributions and realizations (see Supporting Information for all outcomes and variable descriptions). Most experts' subjective probability distributions encompassed the actual values for 3 of the calibration variables: 2011 Lake Erie biomass of walleye (WY11), rainbow smelt (RS11), and round goby (*Neogobius melanostomus*; RG11). All 3 of these variables were supported by long-term (1990–2010) data sets presented to experts before and during the elicitation (Table 3 & Supporting Information). However, uncertainty ranges for WY11 and RS11 were wider than those estimated for RG11, and experts frequently attributed this to the variability observed in the historical data for those species. Calibration variables concerning stomach contents of white bass (WBy11, WBa11) and walleye (RS_WYa11) were considered more complex to estimate by experts (due to potential variability in field sampling or encounter rates by predators). This was reflected in the wide range of expert responses and associated uncertainties.

The EQ combination had a calibration score of $P = 0.3126$, indicating that we would not reject the hypothesis that EQ's probability assessments were accurate. The PB combination also had a good calibration score (0.7606), and both schemes (EQ, PB) returned high information (mean relative information, all variables: EQ 0.5789 and PB 3.798 [Table 2]). Expert 4 received a weight of 1. In roughly one-third of all applications, a single expert received all of the weight. The PB combination (i.e., DM) was better calibrated and more informative than the EQ combination. Thus, the PB significantly outperformed the EQ aggregation of experts' assessments.

For robustness of the DM to individual calibration variables, the loss of any single calibration variable had virtually no effect on the DM (Table 3). The PB weight was always assigned to expert 4 despite the removal of any one calibration variable. Overall, the informativeness and statistical accuracy of the optimized PB DM were very good, and this conclusion was robust against loss of a single calibration variable.

Regarding the robustness of the DM to the presence or absence of individual experts, the effect on the DM by removing an expert other than expert 4 was small (Table 4). Removing Expert 4 induced a mean relative information score (with respect to the background measure) of 2.125. Thus, the loss of expert 4 induced an overall change in the DM that was greater than the effect of removing any of the other experts. Indeed, robustness is not the goal of performance optimization. However, if the results are

Table 1. Information on experts who participated in a structured expert judgment study concerning the biological impact of bighead and silver carp establishment in Lake Erie.

Name*	Title, affiliation, and expertise
Duane C. Chapman, MS	Research fish biologist, United States Geological Survey, River Studies: Invasive Carp Research Program; affiliated with the Asian Carp Working Group, Asian Carp Rapid Response Team, Mississippi River Basin Panel on Aquatic Nuisance Species and the American Fisheries Society
Joseph V. DePinto, PhD	Senior scientist, Limnotech; former professor of environmental engineering, conducts aquatic ecosystem structure and functioning research and designs education and management programs, with emphases on the Great Lakes region
Tomas O. Höök, PhD	Associate professor of fisheries and aquatic sciences, Purdue University, Department of Forestry and Natural Resources, focuses on fish and fisheries ecology in the Laurentian Great Lakes
Timothy B. Johnson, PhD	Research scientist, Ontario Ministry of Natural Resources, Great Lakes Fisheries Division; expertise in bioenergetics models, specifically for Lake Erie and has studied the biology of invasive fish
Roger L. Knight, MS	Lake Erie Fisheries Program administrator, Ohio Department of Natural Resources, Division of Wildlife, serves on the Lake Erie Committee and the Council of Lake Committees (Great Lakes Fisheries Commission)
Stuart A. Ludsin, PhD	Associate professor, The Ohio State University Department of Evolution, Ecology and Organismal Biology; expertise in mechanisms that regulate fish population and community structure and dynamics, food web interactions, and natural resource management
Charles P. Madenjian, PhD	Research fishery biologist, United States Geological Survey, Western Basin Ecosystems Branch, Lake Michigan Section; quantitative fisheries biologist; has focused on fish bioenergetics modeling in the Great Lakes
Peter Meisenheimer, MS	Executive director, Ontario Commercial Fisheries Association; biologist for commercial fisheries interest in Ontario; member of the Canadian Committee of Advisors of the Great Lakes Fishery Commission; Chair of the Ontario Species at Risk Public Advisory Committee
Mark A. Pegg, PhD	Associate professor, School of Natural Resources, University of Nebraska Lincoln; specializes in fisheries management, impacts of aquatic nuisance species including Asian carps, and restoration ecology
Kevin Reid, MS	PhD candidate, University of Guelph, and assessment manager and fisheries biologist-technical advisor Ontario Commercial Fisheries Association
Brian J. Shuter, PhD	Professor, Department of Ecology and Evolutionary Biology, University of Toronto, Research Scientist Aquatic Research & Development Section Ontario Ministry of Natural Resources; focuses on food web dynamics, population ecology, and growth and production models for fish and zooplankton

Expert names are not associated with responses in the public documentation of the study, but this association is preserved in internal records. This policy shields experts from intrusive questioning while allowing for competent scientific review. Thus, the ordering of the experts presented here is alphabetical and does not correspond to the ordering of results.

not robust, this would indicate there may be artifacts affecting performance. This provides the analyst a cause to further assess model performance. Even without expert 4, the calibration and overall informativeness scores and the PB DM were still good (2.125 and 0.666, respectively [Table 4]) and better than the equally weighted DM. The difference between the original and recalculated DM was comparable to the differences among the experts themselves, as measured by the mean relative information to the EQ DM. Thus, in this case, all DMs were robust to the removal of any individual expert.

Asian Carp Biomass

Peak biomass (5th, 50th, 95th percentile of the PB combination) for bighead (1.56, 8.93, 25.90 t/km^2) and silver (1.56, 8.83, 25.90 t/km^2) carp in scenarios in which they were sole invaders were higher than equilibrium biomass estimates (0.39, 3.04, and 12.18 t/km^2 & expert estimates were the same for both bighead and silver) (Fig. 2). The

EQ combination estimates were lower than the PB combination estimates for both bighead (0.00, 2.54, 17.00 t/km^2) and silver (0.01, 2.50, 19.10 t/km^2) carp. In the joint invasion scenario (bighead + silver), equilibrium biomasses were equivalent to the equilibrium condition values estimated for bighead and silver carp alone for the PB combination. However, for the EQ combination, the median and 95% estimates for biomass in the joint invasion scenario were higher than when either of the species established alone.

Experts had greater certainty (e.g., narrower uncertainty range) about equilibrium values of Asian carp biomass relative to peak values. Median equilibrium values were approximately one-third the magnitude of median peak values (PB combination: 3.04 vs. 8.83–8.93 t/km^2). However, both equilibrium and peak carp estimated median biomasses were equal to or greater than the sum of observed yellow perch, stwalleye, rainbow smelt, and gizzard shad biomass in Lake Erie in any

Table 2. Performance and combination of expert judgments for a structured expert judgment study concerning the potential biological impact of bighead and silver carp establishment in Lake Erie.

Expert	Calibration score[a]	Mean relative information[b] All variables	Calibration variables	Normalized weight
1	0.1815	1.395	0.6121	
2	0.1227	0.677	0.6648	
3	0.0056	2.832	1.4700	
4	0.7606	3.798	0.8562	
5	0.6660	2.148	0.8400	
6	1.93E-06	1.481	1.3810	
7	0.0595	1.839	1.1580	
8	0.6150	4.334	1.0860	
9	0.5276	2.547	1.2880	
10	0.2587	2.603	0.8282	
11	0.5276	2.517	0.8071	
EQ[c]	0.3126	0.5789	0.2943	0.0920
PB[d]	0.7606	3.798	0.8562	0.6513

[a]*Likelihood that the realizations of calibration variables correspond with the expert assessments.*
[b]*Measure of the degree to which an expert's uncertainty distribution is concentrated around the true answers to a set of variables (either to all variables [3rd column] or to the calibration variables [4th column]).*
[c]*All experts' responses pooled with equivalent weights to form an equally weighted (EQ) combination called a decision maker (DM).*
[d]*Experts' judgments weighted according to a selected cut-off level for calibration for which the normalized weight (5th column) of the combination is maximal. This combination is called the performance based (PB) decision maker (DM).*
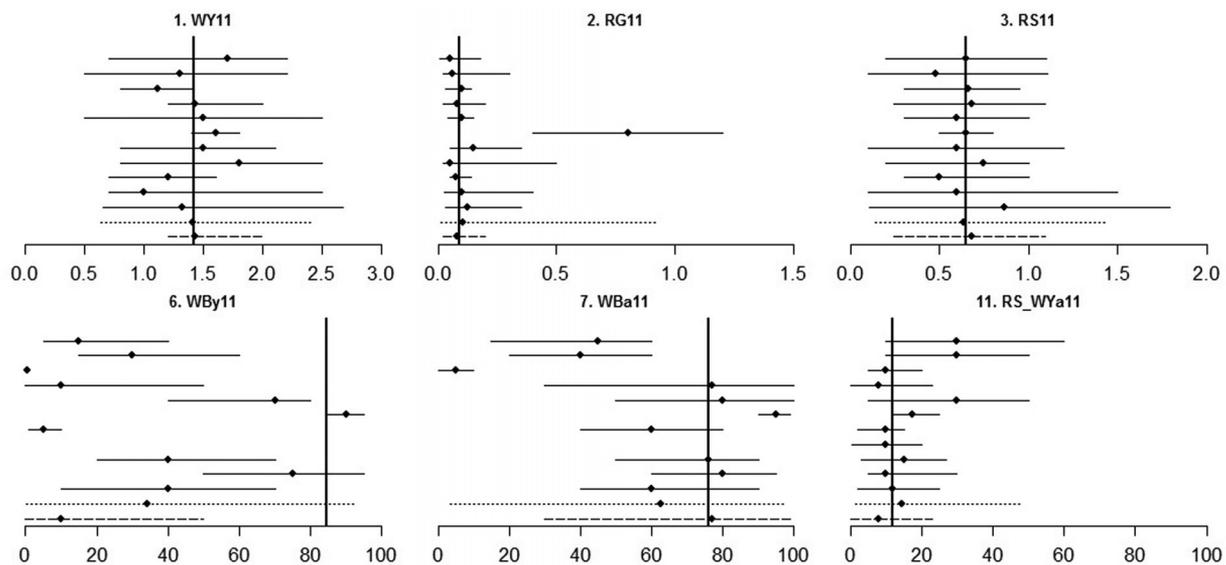
Figure 1. Expert and decision maker (DM) (i.e., combination of expert judgments) uncertainty ranges for a subset of the calibration variables used in the study of bighead and silver carp establishment and impact in Lake Erie: top row, 2011 Lake Erie whole lake biomass (t/km^2) of walleye (WY11), Central Basin biomass of round goby (RG11), and whole lake biomass of rainbow smelt (RS11); bottom row, 2011 Lake Erie Central Basin annual percentage of fish in diet of yearling white bass (WBy11), percentage of fish in diet of (2+) white bass (WBa11), and percentage of rainbow smelt in diet of (2+) walleye (RS_WYa11) (dotted lines, equal weighted DM; dashed lines, performance weighted DM; vertical line, true realization of calibration variable value). See Supporting Information for realizations and detailed descriptions of all calibration variable values.

year between 1990 and 2011. To estimate bighead carp biomass (peak and equilibrium), most (8/11) experts referred to the long-term Lake Erie fish biomass record and the primary literature. Specific methodologies for

estimating carp biomass varied from using peak or average observed values for other taxonomic groups to using adjusted estimates of Asian carp biomass in other systems according to environmental parameters in Lake Erie.

Table 3. Robustness analysis on calibration variables (used to evaluate individual expert performance) showing the result of removing calibration variables one at a time and recalculating the performance-weighted decision maker (DM; the combination of expert judgments).*

Calibration variable removed	Mean relative information	Calibration scores
WY11	0.856	0.659
RG11	0.800	0.659
RS11	0.880	0.659
GS11	0.856	0.659
SMBa11	0.791	0.659
WBy11	0.867	0.399
WBa11	0.894	0.659
YPy11	0.783	0.659
YPa11	0.871	0.659
RS_WYy11	0.859	0.659
RS_WYa11	0.858	0.659
RG_WYy11	0.886	0.659
RG_SMBa11	0.881	0.659
RG_YPa1	0.874	0.659
pool12	0.889	0.659
None	0.856	0.661

*This analysis includes all 15 calibration variables and does not apply to the case in which expert judgments were equally weighted. Mean relative information (column 2) and calibration scores (column 3) of the new decision maker obtained by leaving out the corresponding calibration variable (column 1). Expert 8 was removed from this analysis, and there are 15 effective seed variables, whereas the original analysis presented in the text had 11 effective seed variables to account for the nonresponses of expert 8. For detailed definitions of mean relative information, calibration scores, and decision maker and a full listing of all calibration variables see Methods and Supporting Information.

Table 4. Robustness analysis showing the result of removing individual experts one at a time and recalculating the performance-weighted decision maker (DM; the combination of expert judgments).*

Expert removed	Mean relative information	Calibration scores
1	3.788	0.7606
2	3.653	0.7606
3	3.794	0.7606
4	2.125	0.6660
5	3.792	0.7606
6	3.775	0.7606
7	3.798	0.7606
8	3.787	0.6610
9	3.755	0.7606
10	3.784	0.7606
11	3.790	0.7606
None	3.798	0.7606

*This analysis does not apply for the equal-weighted decision maker (DM). Mean relative information (column 2) and calibration scores (column 3) of the new DM obtained by leaving out the corresponding expert (column 1).

Supporting Information contains expert assessments of production to biomass (P/B) and consumption to biomass (Q/B) ratios and detailed rationales for these and Asian carp biomass estimates.

Asian Carp impact on other Lake Erie Fishes

Both the PB and EQ combinations reflected experts' estimates of minor impacts from Asian carp (bighead + silver) establishment to Lake Erie yellow perch, walleye, rainbow smelt, and gizzard shad biomass (Fig. 2). Uncertainty ranges for these variables were substantially narrower than those forecasted for Asian carp biomass. Biomass estimates for walleye (PB: 0.87, 1.29, 2.21 t/km^2 & EQ: 0.12, 0.78, 2.17 t/km^2) encompassed the 2011 (1.42 t/km^2) and the long-term (1990–2011) average (1.40 t/km^2) biomass realizations. Four experts did not think Asian carp would impact walleye biomass (relative to the 2011 realization), and 7 indicated there would be a very slight negative impact, due to competition for habitat and food. In contrast, yellow perch biomass (PB: 1.00, 1.16, 1.50 t/km^2 & EQ: 0.13, 0.67, 1.41 t/km^2) was estimated to increase relative to both the 2011 (1.00 t/km^2) and long-term average (0.79 t/km^2) realizations. Most experts suggested that yellow perch have a wider niche in Lake Erie due to their omnivory and ability to occupy deeper waters, which enable this species to avoid competitive pressure resulting from Asian carp establishment. Despite the overlap with Asian carp in trophic status, diet, and habitat, gizzard shad biomass (PB: 0.03, 0.17, 0.62 t/km^2 & EQ: 0.00, 0.15, 0.83 t/km^2) was not expected to differ greatly from its 2011 (0.27 t/km^2) or long-term (0.38 t/km^2) biomass realizations. Six of 11 experts expected gizzard shad to decline in the presence of Asian carp, whereas 5 expected shad biomass to remain similar to its 2011 biomass. This disagreement was motivated by differences in opinion about food availability as a limiting factor and resource competition between Asian carps and shad. Similarly, rainbow smelt biomass (PB: 0.25, 0.61, 1.09 t/km^2 & EQ: 0.06, 0.36, 1.23 t/km^2) was not expected to change much as a result of Asian carp establishment relative to the 2011 (0.65 t/km^2) or long-term averages (0.56 t/km^2). Six experts indicated that smelt biomass would not change, and the remaining 5 indicated its biomass would shift (either increase or decrease). Experts who expected no change reasoned that there would be little competition between rainbow smelt and Asian carp due to different feeding preferences.

Discussion

Forecasting species invasions exemplifies the challenges of ecological forecasting and natural resource management in the face of scientific uncertainty. Because the decision to invest in any invasive species management strategy is dependent on the ecological and economic impacts of the invader, uncertainties about these impacts can lead to inaction, delayed action, or even too much action by policy makers and managers. These inefficiencies may lead to significant decreases in ecosystem
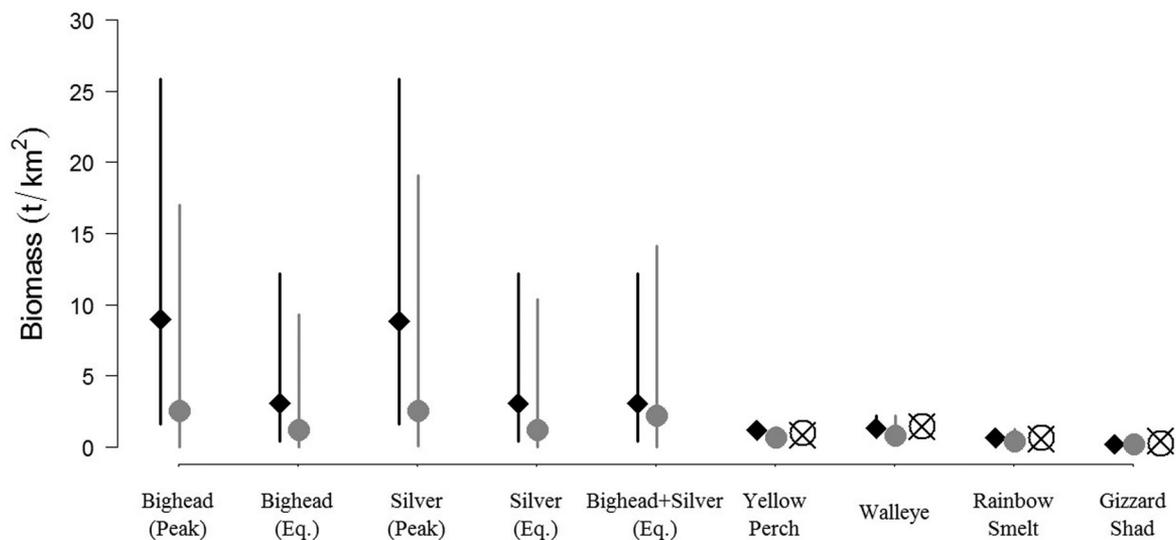
Figure 2. Performance based (black lines and diamonds) and equal weighted (gray lines and circles) combination distributions for expert estimated Asian carp, yellow perch, walleye, rainbow smelt, and gizzard shad biomass in Lake Erie if bighead and silver carp were to establish (diamonds and circles, 50th percentile; line ends, 5th and 95th percentiles). Estimates are shown for peak (Peak) and equilibrium (Eq.) ecosystem conditions. Recent (open circle, 2011) and long-term average (x, 1990–2010) biomasses are shown for each of the 4 Lake Erie fish evaluated by experts.

services provisioning and social welfare (Shogren 2000; Finnoff et al. 2005). Despite the regulatory, technological, and scientific progress that has occurred with respect to invasive species research and management, scientists and managers still have a wide range of opinions about what Asian carp, and other nonindigenous species, may do next.

When policy makers turn to scientific experts for advice in such scenarios, achieving consensus is difficult because intrinsic scientific disagreement is heightened by diversity of expertise, divergent professional interests, and communication barriers (Martin & Richards 1995). This study is no exception: experts provided highly variable forecasts of Asian carp invasion risk and of the ecological mechanisms by which this risk may occur. However, when the SEJ method and PB metrics are used to quantify uncertainty, neither researchers nor policy makers are forced to require or impose consensus among experts and their conceptual models. Thus, SEJ is a process that protects the experts by separating expert identity from individual responses and protects the DM by providing an empirically controlled PB metric as an inclusive and transparent approach that takes into account multiple opinions.

One potential concern with the SEJ method, however, is that it relies on the assumption that performance on calibration variables predicts performance on the variables of interest, for which realizations are not known. This illustrates the importance of not just expert selection, but calibration variable selection as a key issue in evaluating a problem or topic with SEJ. For example, interdisciplinary

problems, such as those often encountered in conservation settings (e.g., habitat conservation, species recovery planning), require experts from multiple backgrounds to properly address the issue. As a result of variability in professional background and training, experts may differ in their abilities to respond to calibration variables, depending on the number and selection of these variables (Cooke et al. 1988; Hanea et al. 2010; Eggstaff et al. 2014).

Our results with both the EQ and PB weighting schemes indicated that both bighead and silver carp can successfully establish in Lake Erie and have the potential to achieve biomass levels similar to or greater than other Lake Erie taxa of similar trophic levels. These results provide the first quantitative forecast of Asian carp impact to the Great Lakes and suggest that bighead and silver carp may assimilate into the Lake Erie ecosystem with little effect on the $18.5 million (USD) yellow perch, $6.8 million walleye, $0.7 million rainbow smelt, and $0.06 million gizzard shad binational commercial fisheries (Ontario Ministry of Natural Resources 2011; USGS 2011). Further, the recreational fishery of Lake Erie also carries considerable economic value: 43% of annual U.S. Great Lakes recreational angling days are spent on Lake Erie, and 20% of all Canadian Great Lakes anglers allocate their effort to Lake Erie (US Department of Interior (USDOI) 2011; Rothlisberger et al. 2012). Our results not only quantify the uncertainties associated with the potential establishment of these species in Lake Erie, but may also serve to clarify and guide future research efforts concerning the dynamics of Asian carp establishment in the Great Lakes.

In contrast with other forecasts, our results indicate that significant negative impacts to the Lake Erie fish community are unlikely. Although establishment risk in Lake Erie is estimated to be high here and in previous studies (Cudmore et al. 2012; Cuddington et al. 2014), previous estimates that the ecological impact of bighead and silver carp would be high in the Great Lakes (Rasmussen et al. 2011; Cudmore et al. 2012) have generally been extrapolated from observations of established river populations, such as the Illinois River, where Asian carp have had unwanted impacts to both ecological communities and recreation (Irons et al. 2007).

There remains the need to resolve the difference between experts' estimates of established Asian carp biomass (which may be large) and the estimated general lack of impact to other Lake Erie fishes. First, many experts based their estimates of Asian carp impact on Lake Erie fish biomass on the average, median, or standard deviation of long-term biomass data records for these species and used these data to define their 90% confidence interval. These experts rationalized that it would be unlikely that a perturbation caused by the introduction of Asian carp would exceed these values. Some experts suggested that the lack of temporal and spatial overlap, and thus lack of competition, between Asian carp and the 4 fish considered was a key factor in estimates of minor impact. Experts also indicated that food availability (e.g., phytoplankton, zooplankton, and detritus) is not and would not become limiting in Lake Erie, even after accounting for the expected consumption of resources associated with Asian carp establishment.

An examination of estimated bioenergetics (P/B, Q/B) ratios (Supporting Information) also may inform elements of ecosystem functioning and trophic dynamics that may not be apparent or directly linked to expert assessments of target variables relating to biomass. For example, the PB combination (DM) for bighead and silver carp Q/B ratios ranged from 0.503 to 60.83 (e.g., 90% CI of PB DM). In a Chinese reservoir dominated by and stocked with Asian carp, Q/B ratios were estimated to be 7.53 for bighead and 10.19 for silver (Liu et al. 2007). The wide range of the PB DM confidence interval for this variable suggests that Asian carp could have a significant impact on energy transfer between trophic levels and may in fact have unprecedented production or consumption rates, relative to their biomass, potentially causing unanticipated perturbations to the Lake Erie food web. The values we report here could be used to investigate (e.g., via the use of food web or trophic interaction modeling) how these bioenergetics ratios may affect ecosystem-level functioning.

Our results do not comprehensively quantify the potential effects of Asian carp on angling or other recreational activities. Even if biomasses of the fishes important to anglers and commercial fishers remain high, silver carp leaping behavior may alter the recreational experience and activity patterns of personal watercraft users, charter fishing boats, and recreational anglers in the Great Lakes. Further, we did not address other potential mechanisms and locations of impacts (e.g., tributary rivers) or direct impacts on the lower trophic levels of Lake Erie. An assessment of the impacts of Asian carp establishment on other Great Lakes use values and connecting water bodies is necessary for a complete risk analysis.

Although our results are specific to Asian carp and Lake Erie, this approach can serve as the framework for addressing the scientific unknowns associated with species invasions or any novel environmental risk. SEJ provides problem owners with a transparent decision support tool in which quantitative assessments are subject to empirical quality controls (Aspinall 2006). Budget constraints associated with natural resource management coupled with the accelerating frequency and complexity of imminent environmental problems will increasingly require conservation biologists to seek out rapid, cost-efficient, and information-rich techniques for risk analysis. As demonstrated here, SEJ is one such technique that offers valuable insights for resource managers and also points the way for future research to reduce uncertainty about pressing environmental threats.

Acknowledgments

Supporting Information

Description, expert assessments, and realizations of calibration variable questions (Appendix S1), detailed explanation of the structured expert judgment method (Appendix S2), expert elicitation protocol and questionnaire (Appendix S3), and expert responses and rationales for target variables (Appendix S4) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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