Aquatic Invasions (2012) Volume 7, Issue 4: 567–575
doi: http://dx.doi.org/10.3391/ai.2012.7.4.013

Open Access

Research Article

Mitigating uncertainty using alternative information sources and expert judgement in aquatic non-indigenous species risk assessment

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Received: 26 September 2011 / Accepted: 3 October 2012 / Published online: 10 October 2012

Handling editor: Thomas Therriault, Fisheries and Oceans Canada, Canada

Abstract

Aquatic non-indigenous species (ANS) management employs risk assessment as a tool to prioritize prevention and control efforts, but timely and comprehensive risk estimates are difficult due to various sources of uncertainty, particularly knowledge gaps. Several fields use or endorse the use of precaution, as well as group Delphic processes, to mitigate this uncertainty. To test the application of these methods in ANS risk assessment, we surveyed the knowledge and attitudes held by ANS scientists and managers regarding uncertainty and involved these experts in a modified Delphic process to determine consequence for a suite of 10 ANS. We found that participants supported the application of precaution in risk assessments. We also found the Delphic process aided the risk assessment process by facilitating outcomes that are supported by experts and stakeholders involved, account for uncertainty, and are therefore useful for policy and management purposes. Finally, we provide several recommendations for mitigating uncertainty in consequence assessments. These outcomes and recommendations provide increased understanding of the presence and sources of uncertainty, and the potential use of precaution and Delphic processes to facilitate the completion of comprehensive biosecurity risk assessments, despite the challenges posed by existing knowledge gaps in ANS impact information.

Key words: non-indigenous species; uncertainty; precaution; Delphic process; risk assessment

Introduction

Aquatic non-indigenous species (ANS) have dramatically affected coastal, estuarine and inland ecosystems via impacts to core values: ecological; economic; socio-cultural; and public health values (e.g., Bolam et al. 2000; Galil 2000; Ross et al. 2002; Verlaque et al. 2004; Neill et al. 2006; Campbell 2009). Aquatic biosecurity risk assessments facilitate efficient and effective ANS management by providing managers with tools to prioritize use of limited resources and thereby reduce the risks of ANS entering, establishing, spreading, and having impacts (Hayes 2003; Campbell 2009; Cliff and Campbell 2012).

Risk is comprised of the likelihood of an adverse event occurring and the consequence or impact of that event (Klinke and Renn 2002). Herein, 'consequence assessment' refers to the assessment of potential impacts posed by a threat and which is combined with a likelihood assessment to produce a risk estimate. The term 'impact' refers to an environmental, economic, social, human health, or cultural effect caused by ANS that contributes to the formal consequence assessment. Evaluating the consequence(s) can be made via direct assessment of empirical data, or heuristic assessment by experts and/or stakeholders that is either used directly or assessed by a trained risk assessor (Campbell 2008, 2009; Hewitt et al. 2010).

Uncertainty in risk assessment

Due to the predictive nature of risk, uncertainty is an inherent component of risk assessment (Morgan and Henrion 1990). This uncertainty can stem from a variety of factors, including: (1) knowledge gaps; (2) systematic and random measurement error; and (3) variability (e.g., Klinke and Renn 2002). Efforts to address uncertainty are an essential element to the risk assessment process itself that can improve the risk assessment outcomes, lead to a greater overall understanding of the risk, and guide research effort and management decisions (Pollack 2003). While expert judgement is often the most appropriate method to make consequence and risk estimates under conditions of uncertainty (Halpern et al. 2007), this judgement is preferably combined with empirical evidence. However, when knowledge gaps force experts to rely on other means to make decisions, experts have several options, including the use of alternative information sources and precaution. Precaution is most commonly defined as: “Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation” (United Nations General Assembly 1992).

While the use of alternative information sources is neither novel nor uncommon for many risk assessors, the World Trade Organization Sanitary and Phytosanitary (SPS) Agreement Article 5 mandates *science-based* risk assessments for any SPS measures that may restrict trade (WTO 1995). As such, these sources must be considered conducive to a science-based risk assessment if the resulting policies potentially affect trade (e.g., mandatory hull cleaning). To this end, the study will gather expert opinions on the validity and appropriate use of various information types.

The use of precaution can also cause controversy in a trade context. In near or complete absence of data, management of ANS generally must take one of two contrasting approaches: assume a species is “guilty until proven innocent” (herein, the “precaution” approach) or assume a species is “innocent until proven guilty” (as suggested by the WTO; Hewitt and Campbell 2007). Organizations vary in adoption of these approaches and several WTO disputes have been based on the application of precaution (Cheyne 2007). This study will gather views of expert scientists and managers on precaution and related actions to guide the incorporation of this element into assessment and related management.

In response to the challenge of identifying and mitigating uncertainty in risk assessment, this study has two objectives. First, it aims to understand the perceived presence and implications of uncertainty in the consequence component of ANS risk assessment, as well as elicit views on tools to address that uncertainty. Second, it aims to contribute to current methods for eliciting expert judgement in consequence assessment of ANS.

Methods

This study used both written survey and group discussion (Figure 1) with two different groups of ANS experts, scientists and managers. ‘ANS scientist’ includes any individual involved in empirical research of ANS; and ‘ANS manager’ includes any individual involved in decision or policy-making and management of ANS. This research was conducted in the United States (US) and Australia (AU), as both countries have relatively extensive ANS research and policy programs, which allows sufficient sample size.

The consequence assessment occurred in three stages to allow comparison of how assessment changed with additional data and group discussion for 10 species (Figure 1). For each consequence assessment, participants rated impacts to each core value and the uncertainty associated with that assessment. Impacts and uncertainty were rated qualitatively (1-5; negligible-extreme), as determining semi-quantitative thresholds were beyond the scope of the study.

For the five actual species, the provided information was based on primary (peer-reviewed) and secondary literature (e.g., government reports and databases such as NIMPIS (NIMPIS 2009) and NEMESIS (Fofonoff 2003)). For the five hypothetical species, the provided information was modelled after one or a combination of actual species in the respective taxa. Impact information for each species was directed at one ‘focus’ core value (i.e., environmental, economic, social/cultural or human health).

Group assessment occurred via a modified Delphic process, a method developed to make decisions and predictions under uncertainty. The traditional Delphic process allows expert revision of judgment based on anonymous input from other experts to reach consensus where possible, and identify areas of disagreement where consensus is not possible. A modified Delphic process uses direct discussion, no required consensus and analysis of uncertainty to improve on traditional methods (Webler et al. 1991). When assessing consequence, the

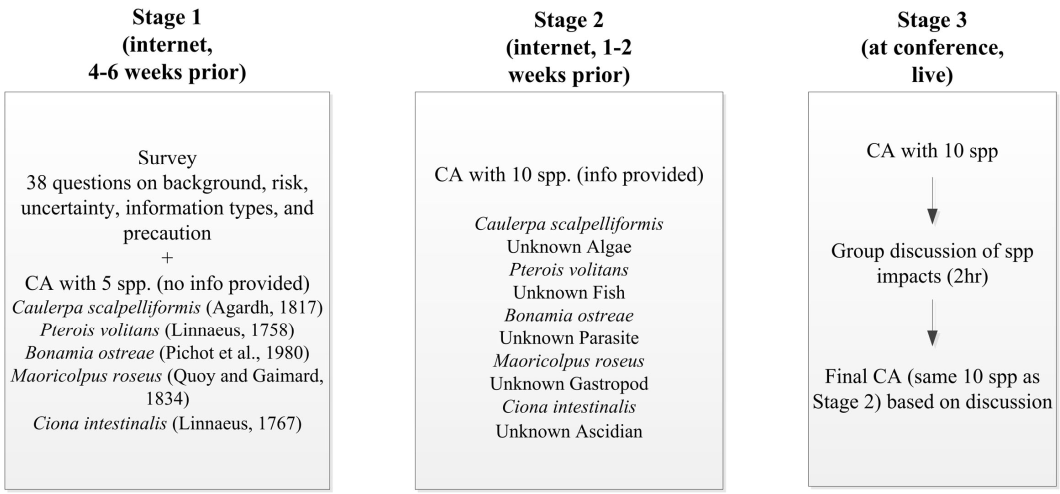

Figure 1. Three stages of survey and consequence assessment (CA).

modified Delphic process facilitates decision-making based on knowledge from a variety of experts and/or stakeholders, which can lead to increased acceptance of the risk assessment outcomes and facilitate the process of risk communication (Beale et al. 2008).

As participants were a specific, often limited, group, we used non-random purposive sampling (Tongco 2007; Gillham 2008) to select experts in the ANS field. Given that participants needed to gather in one location for the workshop, as well as the limited funding and busy expert schedules, the workshops were held in conjunction with four conferences on ANS issues. Thus, recruitment was based on conference attendees for both scientist and management groups. Invitations and announcements for the surveys and workshops occurred through conference organizers. Those that participated in the surveys were invited to participate in the workshop, but attendance was not mandatory and thus these two components were analysed separately. The United States/Canada (US/CA) scientists were sampled during the 6th International Conference on Marine Bioinvasions held in Portland, OR, USA from 24-27 August, 2009. Although we targeted US participants, several participants were currently working or had trained in Canada. As such, we included Canada in the group description. The Australian (AU) scientists were sampled during the Australian Marine Sciences Association Annual Conference held in Wollongong, NSW, Australia from 4-8 July, 2010. The US/CA managers were sampled during the International Conference on Aquatic Invasive Species held in San Diego, CA, USA from 29 August-2 September, 2010. The AU managers were sampled during the Australian National Introduced Marine Pests Coordination Group meeting in Canberra, ACT, Australia from 1-2 December, 2010.

Ethics approval was obtained from the Tasmania Social Sciences Human Research Ethics Committee (reference number H10726). At all times during this research the Australian National Statement on Ethical Conduct in Human Research was complied with. To maintain confidentiality, participants were provided with a participant number to use during the project, instead of personal name. While anonymity was lost during group discussion (as participants met face to face), analysis and reporting of results remained anonymous. If desired, participants could elect to withdraw from the study. However, no participants chose to withdraw.

Responses to survey questions on background, uncertainty, information sources and precaution were summarized using descriptive statistics. Summary and thematic analyses were used to determine how the modified Delphic process affected the participants' assessments of consequence for the 10 ANS. Mean consequence and uncertainty ratings were summarized at each stage, for each core value of the 10 species. Thematic analysis, using group discussion and written comments during the modified Delphic process, identified recurring patterns (Patton 2002). Group leadership dynamics were assessed via counts of individual participant comments, questions directed towards participants and reference to participants comments.

Results

A total of 84 individuals responded to the surveys (27 US/CA scientists, 17 AU scientists, 27 US/CA managers, 13 AU managers). A total of 60 individuals participated in the workshop (71% of those surveyed; 21 US/CA scientists, 12 AU scientists, 13 US/CA managers, 14 AU managers). Each group exhibited only slight differences so are summed across groups below.

Attitude toward and knowledge of uncertainty (survey)

Most participants (94%) agreed with the existence of 'unknown unknowns' (i.e., uncertainty that is not or cannot be described). Slightly more participants felt that *few* research questions could be answered with high certainty (51%) than those that felt that *most* research questions could be answered with high certainty (35%). Most participants (86%) indicated that uncertainty is unavoidable but can be managed to provide reliable results. The questions on knowledge gaps indicate that almost all participants (96%) felt that ANS have an impact due to their presence as a non-native component of the ecosystem, and of these, many (80%) felt that assigning a 'low' impact is appropriate if there is an absence of impact information for that species. Other common sources of uncertainty in ANS assessment identified by the participants in the open-ended questions included a lack of baseline knowledge, the effects of climate change, and predicting to what extent species will become invasive, particularly due to different ecological conditions (abiotic and biotic).

Most participants (79%) agreed that avoiding Type II errors is more important than avoiding Type I errors when assessing ANS impacts. When data is associated with an insignificant *p*-value, many (71%) also felt this data may be used with discretion if no other data is available and about a quarter of participants (24%) felt it valid to use when assessing impact. When asked when past impacts are appropriate to use as predictors of future impacts for ANS, about half (52%) of participants chose 'most of the time' and about half (48%) chose 'some of the time'.

Information types (survey)

In the absence of peer-reviewed literature, participants most frequently rated 'supported/ verified observations' as the first alternative source of information, followed by 'heuristic/ expert observation/experience' and 'personal communication with scientist' (Table 1).

Attitude toward and knowledge of precaution (survey)

Most individuals felt that precaution is a necessary component of a risk assessment (87%); should be applied along a continuum, with greater potential threats requiring less certainty before taking precautionary measures (74%); and felt that the application of precaution included using all types of information (even non-scientific; 79%). Participants most frequently rated "in the final assessment, include even those species with low and/or unknown likelihood or low and/or unknown impact designation as possible risks" as a potential way to incorporate precaution into a risk assessment, followed by "when assessing impacts for a species using previously-documented impacts, use the impact of highest magnitude" (Table 2). Finally, most participants felt that the provided WTO SPS Article 5.7 text on provisional action would suggest the use of precaution as a tool in risk assessment (80%).

The modified Delphic process (workshops)

Each workshop group broke into three smaller groups ('subgroups'), except for AU scientists (two subgroups). Of the eleven subgroups, review of conversation suggested most had dominant male leaders with moderate (5-10 years) to high (10+ years) experience. Analysis of discussion from each workshop revealed themes common to several of the groups (Table 3).

Discussion

This study identifies and maps the presence of uncertainty, as well as attitudes toward uncertainty and precaution within ANS risk and consequence assessment. The outcomes re-iterate the substantial presence of uncertainty in ANS risk assessment (e.g., Grosholz and Ruiz 1996; Barry et al. 2008). Specifically, participants identified gaps in understanding of ANS as a significant challenge to ANS risk assessment. As

Table 1. Summary of responses to questions related to information type.

When assigning impacts for non-indigenous species with absent or insufficient peer-reviewed impact data, it is appropriate to also include (choose all that apply):	Frequency chosen
Supported/verified observations (e.g. data from more than one person involved in resource management such as restoration planners or park director)	73
Heuristic/expert observation/experience	69
Personal communication with scientist	67
Lay knowledge (e.g. observational data from public such as port managers, long-term residents of a site, or fishers)	57
Impacts that are published but do not cite experimental analysis	47
Grey literature (e.g. websites, policy documents, databases, reports)	46
Incomplete and/or unfinished scientific studies	46
“Anecdotal” information, such as news stories	16
Unsupported/unverified observations	2

a result of these knowledge gaps, participants desired an “unknown” category in the assessment response options (Table 3). However, from a management perspective, assigning a species as “unknown” does not produce a useable outcome (Underwood 1995). In order to provide a policy-relevant risk assessment, experts should provide some estimate of impact with an associated uncertainty rating. As highlighted by the results and suggested by other studies of biosecurity under uncertainty (e.g., Ikeda 2006), this could occur via use of alternative information sources, precaution and group discussion (e.g., a modified Delphic).

While supported/verified observations and lay (non-expert) knowledge are used in some ANS risk assessments, their rank in the top half of alternative information sources (as chosen by ANS experts) is significant in validating them as useable in a science-based assessment. These non-empirical sources, while often highly informative, are not always considered acceptable by those involved in ANS management. For example, the WTO framework is often unsuitable to adaptive governance or related approaches for regulating and managing invasive species under uncertainty (Cooney 2007; Dahlstrom et al. 2010; Dahlstrom 2012).

While non-empirical sources should be examined in the same manner as empirical evidence for quality control, the support by scientists and managers suggests their appropriate use could facilitate more comprehensive risk assessments that still hold up under WTO challenge.

The study also found widespread support by ANS scientists and managers for the use of precaution and options for implementing it. While precaution in risk assessment has been endorsed by various treaties and agreements, few studies have looked at the opinion of those involved in policy (but see Wilson et al. 2006). However, both Wilson et al. (2006) and others related to the current study (Dahlstrom 2012, in review) were limited to scientists and managers and did not include other stakeholders that may have had differing views as to the importance of precaution to protect the environment, and precaution to protect trade and industry. Thus, the outcomes (including the suggested means of implementation) should not be taken as sweeping endorsement of precaution, but instead serve as tools should experts and stakeholders involved decide that precaution is appropriate. The modified Delphic process could aid decision-making in this area.

The modified Delphic process influenced the process and outcome of the consequence assessment in several ways, as evidenced by the identified themes. That uncertainty did not decrease may appear to indicate failure. How, the justification for group discussion is not solely a decrease in uncertainty, but also the identification of uncertainty and facilitation of

Table 2. Summary of participants' views on steps to integrate precaution into a risk assessment.

Description of precautionary steps	Frequency chosen
In the final assessment, include even those species with low and/or unknown likelihood or low and/or unknown impact designation as possible risks	50
When assessing impacts for a species using previously-documented impacts, use the impact of highest magnitude	43
If impacts for a particular non-indigenous species are unknown, use impacts from a similar species with known impacts	42
Including public input regarding values and impact significance	32
Use conservative estimates when developing and/or using model parameters	32
Assume all cryptogenic species are non-indigenous; that is, if a species can't be determined to be native or not, assign non-native status	18
For non-indigenous species with unknown impacts, assign a "low" impact	18

Table 3. Themes repeated in two or more workshops.

Major Theme	Description
Increase in consequence rating	Overall, 27% of assessments increased, 3% decreased, and 70% showed no significant difference in consequence rating after discussion.
No change in uncertainty rating	Overall, no assessments showed a significant difference in uncertainty rating after discussion.
Desire for unknown category	Several participants (particularly in US/CA scientist subgroups) were unwilling to assign impact without additional information, particularly scientific literature. For example, comments such "I didn't want to have to [choose] – I wanted to have an 'unknown' [category]."
Associated economic and social/cultural values	Participants in all workshop groups perceived a relationship between economic and social/cultural (and, to a lesser extent, human health) consequence magnitudes (i.e., social/cultural effects were derived from economic effects).
Location matters	Location of the impact influenced the perceived consequence.
Impacts are relative	Participants proposed using relative scales to assess consequences. For example, "I would like a scale – the 'worst' non-native and the 'least' impactful, and compare it to this scale".
Comfort zone and field-specific assessment	Several of the groups discussed how their field (and associated comfort with associated values) influenced their assessment. Specifically, several participants suggested that their expertise in the environmental field affected their assessment for the other values.

a faster and more comprehensive completion of the consequence assessment with fewer resources due to real-time discussion and variety of input (Krueger and Casey 1994). Additional research in the form of longer discussion times and more/less participants could determine whether these factors may have allowed participants to not only identify uncertainty but also mitigate against it.

While the results provide several useful outcomes, the limitations and potential biases also warrant consideration. The sampling methodology (purposive, self-selecting) and size of this study presents some potential biases and limitations, respectively. While practical, given the pre-identified target audiences and resource limitations, the use of non-probability sampling techniques can introduce biases into the study. The small sample size restricted the potential power and therefore use of statistical analyses. For example, the small sample size precluded generalized conclusions based on Table 3; however, the themes identified over multiple workshops warrant additional investigation. This issue could be addressed with greater sample size and regression techniques (based on interval measurement of experience; e.g., Donlan et al. 2010). This is difficult, however, due to the relatively small numbers of experts in the ANS field, both in the countries included in this study and globally.

A second potential bias results from the survey design. The survey included questions with many agree/disagree-based Likert scale responses that lacked a "neutral" option, and the consequence assessment provided participants with a Likert scale response lacking an "uncertain" or "unknown" option. Although the lack of a "neutral" option has been shown to effect response distributions (Bishop 1987), there are other survey benefits to this approach (Garland 1991). In addition, real-world ANS risk assessment and management require some decision of consequence (as opposed to "unknown" or "uncertain"). The absence of an "uncertain" category (with an allowance for participants to describe their uncertainty, separately) is useful in achieving useful outcomes and thus appropriate for the study.

Despite these limitations, participants identified sources of uncertainty in ANS risk assessment (e.g., gaps in understanding of ANS). As a result of these knowledge gaps, participants expressed a desire for an "unknown" category to be included in assessment/answer options. However, from a management perspective, assigning a species "unknown" does not produce a useable outcome. In order to provide a policy-relevant risk assessment, experts need to provide some estimate of impact with an associated uncertainty rating. Outcomes of this study suggest that in situations of high uncertainty, experts can still provide functional consequence assessments through the use of various information sources (empirical and non-empirical), a Delphic process that includes a variety of stakeholders, and precaution. In particular, group discussion and input benefits the risk assessment process and outcome, via increased diversity of opinion and by highlighting common themes as well as false or extreme opinions (Krueger and Casey 1994). This effect and potential improvement via discussion is seen in other group exercises, when participants interact with and expand upon other participants input to synergistically produce new forms and amounts of knowledge (Litosseliti 2003). Thus, exercises such as the Delphic process can facilitate completion of valid risk assessments despite the challenges posed by uncertainty, aiding more effective management of ANS.

Recommendations

Based on the outcomes of this study we suggest the following recommendations for mitigating uncertainty within a consequence assessment.

When empirical evidence is lacking for a particular ANS at the relevant spatial and temporal scale, alternative information sources can include empirical evidence from other regions or from similar species, as well as non-empirical evidence. Participants advocated using a variety of information sources (even those that are 'non-scientific') to manage uncertainty and produce a consequence assessment and from this, a risk assessment (Table 1).

Precaution, which the participants identified as a necessary and valid tool in risk assessment, can be implemented in ways that support conclusions and recommendations from other components of the exercise. In addition to participants' stated views on the necessity of integrating precaution into a risk assessment, their views on the importance of avoiding Type II errors (over Type I errors) and of considering even 'non-significant' results also supports the initial endorsement of precaution. The endorsement of precaution and its implementation via means described (Table 2), as a response to uncertainty by expert scientists and managers, suggests these elements do not stand opposite or in deliberate ignorance of the scientific process, but are consistent with and direct responses to lessons from invasion biology.

Conclusion

In addition to remaining an essential element of the risk assessment process, understanding the sources of uncertainty provides advantages to the policy application of the assessment. Applications include identification of potential research focus areas, an increase in the transparency of the assessment outcomes and easier revision or adaptation of these estimates for other use (Morgan and Henrion 1990). Outcomes of this study suggest that in situations of high uncertainty, experts can still provide functional consequence assessments through a combination of various information sources (empirical and non-empirical) and precaution. In addition, the modified Delphic process may assist in identifying and mitigating the sources of uncertainty, and should be further explored for better understanding of its role. Finally, given the diversity of consequence and risk assessment scenarios, the specific combination of these tools needs to be discussed and decided by the experts and stakeholders involved.

Acknowledgements

A. Dahlstrom thanks the Australian Maritime College (a specialist institute of the University of Tasmania) for the John Bicknell Research Scholarship, the University of Tasmania for the Postgraduate Research Fund Scheme, and the Australian Geographic Society for a Seed Grant, which provided financial support. A. Dahlstrom also thanks those individuals within each conference that facilitated organization of each workshop: Robyn Draheim (International Conference on Marine Bioinvasions), Narelle Hall (Australian Marine Sciences Association Annual Conference), Lisa Carmody and Elizabeth Muckle-Jeffs (International Conference on Aquatic Invasive Species), and Sonia Gorgula (Australian National Introduced Marine Pests Coordination Group meeting). The authors thank the anonymous reviews and journal editors for valuable comments on earlier versions of the manuscript.

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