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Methods

An integrated decision-support approach in prioritizing risks of non-indigenous species in the face of high uncertainty

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ABSTRACT

When evaluating the risks of future invasions, we often have sparse information on the likelihood that a species will arrive, establish and spread in a new environment, and on the potential impacts should this occur. Conventional risk assessment, therefore, is limited in providing guidance in managing the risk of non-indigenous species (NIS). However, risk management decisions must be made facing these uncertainties to avoid high and irreversible impacts.

We develop an integrated ecological economic modeling and deliberative multi-criteria evaluation (DMCE) approach to support group decision-making in risk prioritization, using an example of ten NIS that could potentially impact Australian plant industries. This innovative approach seeks to combine the advantages of dynamic modeling with the benefits of DMCE in assessing and communicating uncertainty. The model unveils the complexity of the socio-ecological system of biological invasion, with a scenario analysis designed to interactively communicate scientific uncertainty to decision-makers. The DMCE provides a structured approach to identifying stakeholders' key concerns in addressing economic, social, and environmental dimensions of NIS risk explicitly. Functioning as a platform for risk communication, the DMCE also offers an opportunity for diverse views to enter the decision-making process and for the negotiation of consensus consensuses.

1. Introduction

Risk is commonly defined as the product of the likelihood of an event and its potential consequences (Burgman, 2005). In assessing the risks imposed by non-indigenous species (NIS), risk analysts often have little information on the likelihood that a species will survive, establish and spread in a new environment, and on the potential impacts should an NIS invasion occur (Simberloff, 2006). This is particularly true when the potential consequences of an invasion are of a long-term and large-scale nature (Strayer, 2009; Strayer et al., 2006).

Facing these uncertainties in estimating both the likelihood and consequences, researchers have acknowledged the difficulty in applying conventional risk assessment approaches to predicting and managing NIS risk (Horan et al., 2002; Rodriguez-Labajos et al., 2009; Simberloff, 2005). The conventional method, was believed to be viable only when the levels of likelihood and consequences are both low; policy makers were recommended to engage in wide consultation and deliberation when the uncertain level associated with likelihood is high, which is pertinent when consequences are expected to be serious and irreversible. This recommendation also included using scenario analysis to investigate the potential consequences when facing a significant level of uncertainty (British Government's Parliamentary Office of Science and Technology, 2004).

This paper provides the first operational decision-support tool that enables both scenario analysis and stakeholder deliberation in the context of risk management (Fig. 1). We apply an integrated ecological economic modeling and deliberative multi-criteria evaluation (DMCE) approach to facilitate decision-making in prioritizing the risk of ten NIS that have not yet been recorded in Australia. The model captures the dynamics of the socio-ecological system of biological invasion with the capability of running scenario analysis in quantifying the economic costs of NIS. The model is designed within the Stella software environment (Version 9.1, High Performance Systems, Inc., Hanover, New Hampshire, U.S.A.) for use in the DMCE to provide a better understanding of system complexity and to present

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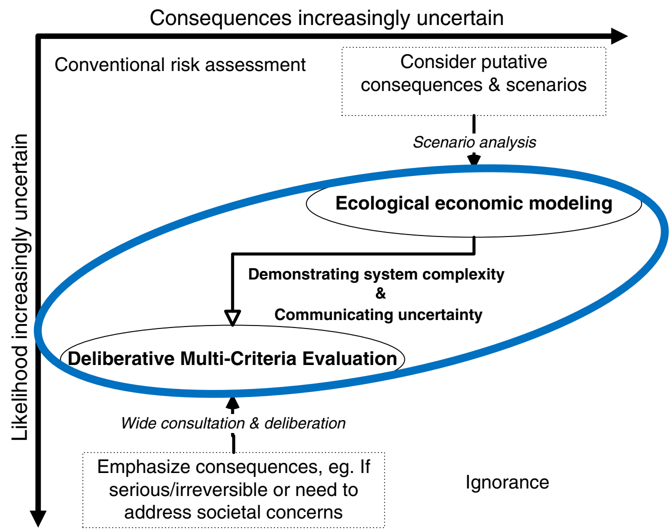

Fig. 1. Using an integrated approach (the largest oval) to facilitate decision-making in prioritizing NIS risks, where an ecological economic model offers interactive scenario analysis and wide consultation and deliberation is structured by deliberative multi-criteria evaluation (DMCE). The model is also used in the DMCE environment to demonstrate system complexity and communicate scientific uncertainty (framework modified from British Government Parliamentary Office of Science and Technology, 2004).

uncertainties in an explicit manner. The DMCE provides an organized analytical approach identifying stakeholders' key concerns and addressing them explicitly and openly. Functioning as a platform for risk communication in which risk analysts, stakeholders, and decision-makers can interact and discuss the uncertainty associated with biological invasions, the DMCE also offers an opportunity for diverse views to enter the decision-making process and for the negotiation of consensus positions.

2. Methodology

Following the risk management framework recommended by the British Government's Parliamentary Office of Science and Technology (2004), we adopted an integrated decision support approach, within which the ecological economic model was used to perform scenario analysis and the DMCE as a platform for wide consultation and deliberation.

2.1. The Ecological Economic Model

The ecological economic model was developed to simulate potential economic costs of NIS invasions. The time over which the model simulates impacts is 30 years (2010–2040). Over time the NIS may enter, establish, and spread in Australia in spite of control, inspection, and eradication efforts at local and national levels. The cost of these management efforts and the loss of market revenue due to infested host plants are estimated based on 1000 stochastic runs of the Stella model. Fig. 2 below presents a conceptual overview of the model structure. Detailed documentation of the model can be found in (Cook et al., 2010).

This ecological economic model has two central characteristics. First, NIS risks are measured in terms of economic cost, including market cost, control cost, detection cost and eradication cost. Second, we designed the model to be used in a DMCE environment as a communication tool for uncertainty. The Stella model accommodates scenario analysis by identifying the consequences of complex interactions among key driving forces and system components. Using DMCE participants' input, an interactive and user-friendly interface capacitates the re-running and re-presenting of economic risks.

Calibrating the model to accurately predict novel states of the system dynamics is a challenge. The application of such models to predict an unknown future may be inappropriate given the potential for perverse model outputs when extrapolating from limited base data (Stainforth et al., 2007). On the other hand, this type of model can be very powerful in communicating uncertainty. It is an effective way to illustrate the point that modeling outputs, based on inbuilt model assumptions and parameter values, should not be taken as the ultimate answers, but rather as guidelines within the larger framework of adaptive management (Costanza and Ruth, 1998).

2.2. Deliberative Multi-Criteria Evaluation (DMCE)

DMCE seeks to combine the advantages of multi-criteria decision analysis (MCDA) in providing analytical structure with the benefits of stakeholder participation (Proctor and Drechsler, 2006). While

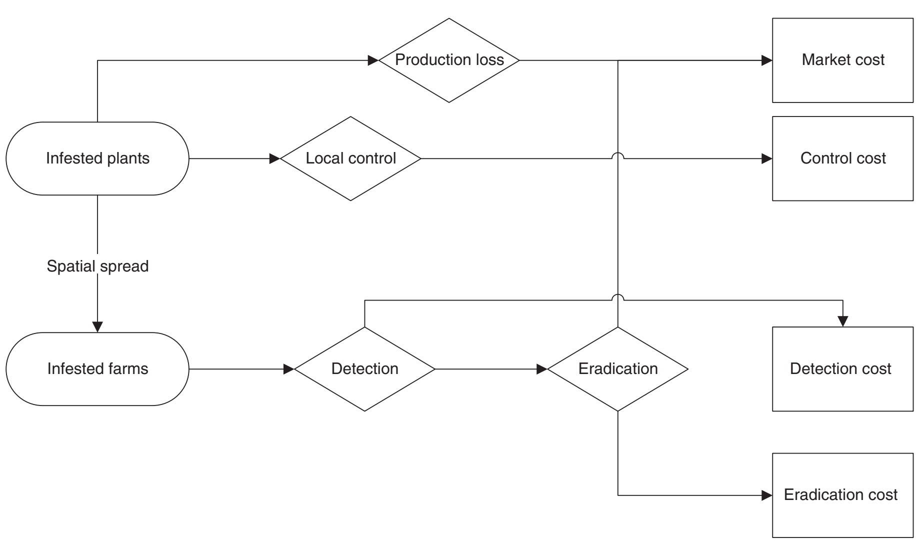

Fig. 2. Overall structure of the ecological economic model in estimating the economic costs of NIS with national significance to Australian plant industries. The time over which the model simulates impact was arbitrarily chosen as 30 years (2010–2040). An NIS will first infect plants at a farm and incur production loss; over time the pest may spread to other farms in spite of management efforts at both local level (e.g. local control such as pesticide application) and national level (detection and eradication). The cost of these efforts and market revenue loss of infested host plants for the NIS are estimated, based on 1000 stochastic runs of the model.

Table 1
The background and interest of the DMCE participants (some of the participants had more than one associations).

Background	Interest
Representative from Plant Health Australia	Coordinating the government-industry partnership for plant biosecurity in Australia
Representative from Apple and Pear Australia Ltd.	Representing the interests of commercial apple and pear growers in Australia in matters of national importance including regulation and legislation, marketing, research and development
Representative from New South Wales Farmers Association	Representing farmers and rural and regional communities in the State of New South Wales
Representative from Department of Environment Water Heritage and Arts	Implementing the Australian Government's policies to protect environment and heritage, and to promote a sustainable way of life
Representative from Department of Agriculture, Fisheries, and Forestry	Developing and implementing policies and programs that ensure Australia's agricultural, fisheries, food and forestry industries remain competitive, profitable and sustainable
Pear grower	Understanding potential biosecurity risk to her farm
Representative from Horticulture Australia Ltd.	Working partnership with Australia's horticulture industries to invest in research, development and marketing programs that provide benefit to industry and the wider community
Representative from Batlow Fruit Co-op	Understanding potential biosecurity risk to their fruit growing industry
Representative from Rural Industries Research and Development Corporation	Increasing knowledge that fosters sustainable, productive and profitable new and existing rural industries
Representative from Cropwatch	Providing growers with timely information on the potential risk of important diseases and pests
Representative from Corporate Research Centre of National Plant Biosecurity	Fostering scientific collaboration and engaging stakeholders to deliver plant biosecurity technologies that will reduce risk to, and ensure sustainability of, Australia's plant industries
Representative from The Commonwealth Scientific and Industrial Research Organisation	Delivering great science and innovative solutions for industry, society and the environment
Representative from Bureau of Rural Sciences	Providing scientific advice that delivers better decisions by Government and better outcomes for rural industries and communities in Australia

traditional MCDA lacks a participatory component, DMCE offers an opportunity for allowing diverse views to enter the decision making process, for facilitating consensus-building, and for initiating a dynamic process of social learning (Rauschmayer and Wittmer, 2006). Only recently have researchers used DMCE in NIS risk management (Cook et al., 2007; Liu et al., 2010).

The DMCE methodology developed in this study is based on the procedure outlined in Proctor and Drechsler (2006). This DMCE uses a public decision-making process involving a citizen's jury based on the model used in English style criminal proceedings. Juries typically range from ten to twenty participants. Ideally the DMCE process uses a facilitator and the jury is given sufficient time to deliberate before a final decision is reached.

The impact matrix (IM) is a critical component of DMCE, containing elements (called impact scores) representing the consequence value for a particular option (in our case, each of the ten NIS) according to a particular assessment criterion (e.g. market cost of each NIS). DMCE participants are then asked to assign weights to each criterion in terms of its relative importance compared to others, with a change in weight indicating a reflective shift of preferences achieved through deliberation.

Although the final outcome of the DMCE is not necessarily a consensus position (Cook and Proctor, 2007), the deliberation process offers an opportunity for consensus-building, which is achieved by focusing the discussion on those criteria for which weights differed the most significantly. Jury members who expressed the minimum and maximum weights for each criterion are asked to discuss their choices. During this process, jurors can reflect on their individual choices and those of other jury members, offering an opportunity to adjust their weights if they feel it necessary.

A key to this structured participatory process is the selection of the stakeholders. We conducted a stakeholder analysis to determine who the key stakeholders in the operating environment were, the interactions among them, the values that were important to them, and what opportunities existed to mobilize their support (Bryson, 2004; Svendsen and Laberge, 2006). The steps in stakeholder selection included an initial survey to assess stakeholders' interest, a follow-up telephone interview to clarify the information gathered in the survey, and application of the snowballing method to expand the number of potential participants (Neuman, 2004; Patton, 2002). We then classified the potential participants by their gender, location (urban vs. rural), scientific knowledge (scientists vs. non-scientists), and background (e.g. government vs. farmer organization representatives). A mix of 12 stakeholders was eventually chosen across different categories of stakeholders. Table 1 below details their background and interests.

Based on results of the stakeholder survey, we selected five criteria in the final analysis: impact on native host range and distribution, environmental health, natural landscape amenity, sustainable rural communities, and economic cost to industry. The impact scores for each criterion-option combination were derived from extensive literature review and expert opinion elicitation, with the exception of economic cost, a major output of the ecological economic model. A detailed description of these criteria is documented in Hurley et al. (2010).

2.3. The Integrated Modeling-DMCE Process

The integration between the ecological economic model and the DMCE was carried out throughout the project (Fig. 3). The two workshops (scoping and trial DMCE workshop) prior to the final DMCE workshop enabled the project team to receive feedback about the effectiveness of the model as a communication tool. The feedback was provided by a group of industry and government representatives, known as the *Expert Reference Panel* (ERP).[1] During the final workshop, the project team reported the uncertainty associated with the impact scores, using the model for scenario analysis in estimating the ten NIS' market cost to industry.

On Day 1 of the decision-making workshop, the project team gave an overview of the ecological economic model as part of the expert testimony in explaining how the impact scores were estimated. After the expert presentations and the subsequent discussion, the jury was asked to provide a relative weighting of the five assessment criteria to reflect each of the importance. The participants and expert witnesses then took part in deliberation, based on a presentation of their mean weights and the standard deviation (SD) of the individual weights. In particular, those jurors who assigned extreme weights among the

[1] The ERP was formed to maximize opportunities to deliver project outputs that could be easily absorbed by our stakeholder industries. Members of the panel provided us with valuable strategic direction in terms of how best to engage stakeholders and present information that they could understand and use to prioritize EPP threats. The ERP is distinct from our DMCE stakeholder jury, although a number of individuals were common to both.

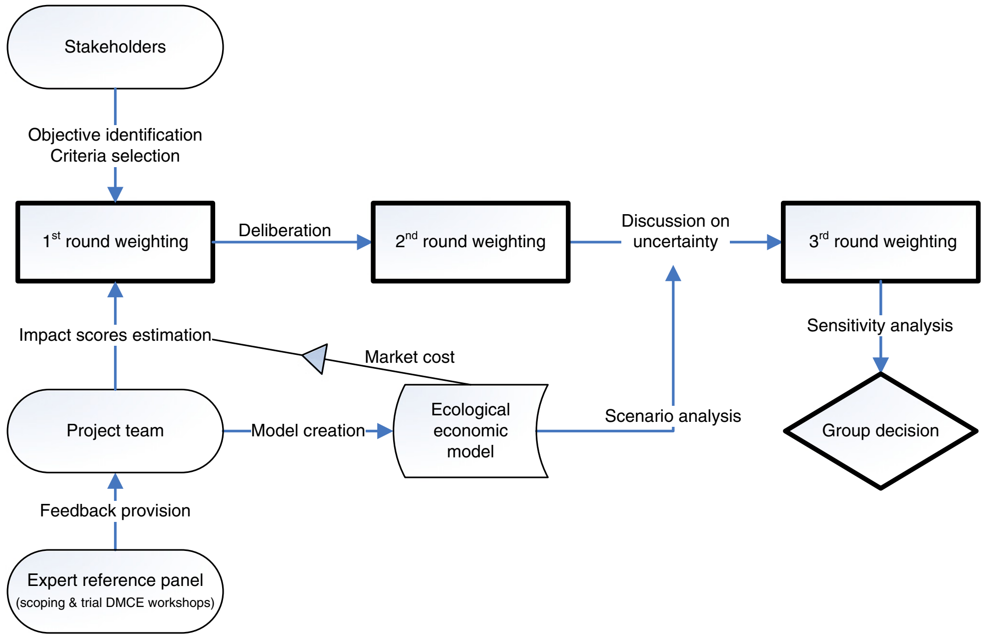

Fig. 3. The integrated modeling-DMCE processes (the steps of the final DMCE workshop are highlighted by bold frames).

group were asked to explain their rationale. A second round of weighting was conducted following the deliberation.

Up to Day 2 of the DMCE workshop, the project team had not made the uncertainty associated with the impact scores known to participants, nor had the discussion specifically addressed uncertainties. On Day 2, the project team delivered a presentation that revealed various sources of uncertainty associated with the economic costs simulated by the ecological economic model. At the ERP's suggestion during the first two workshops, we attempted to accommodate DMCE participants' differences in numeracy capability by presenting the simplest scenario analysis possible. A "double-trouble" scenario was described, in which the ten NIS were assumed to spread more quickly and with a reduced budget for control, compared to the base-line scenario estimates presented on Day 1. The project team then revealed the potential economic costs for the two scenarios side by side, showing that the market cost could be up to 14 times as high under the "double-trouble" scenario (although for six out of the 10 NIS there was no significant difference between the two scenarios). The third round of weighting was then carried out after the uncertainty presentation and a related discussion.

Following this third and final round of weighting, a sensitivity analysis was conducted. It served the dual purposes of communicating the aggregation method to the workshop participants and determining the influence of impact scores and weights on the overall risk ranking. We were able to run and present different scenarios suggested by the participants, using the interactive and user-friendly interface of the ecological economic model.

We used MCAT (multiple criteria analysis tool) (Marinoni et al., 2009) for conducting the sensitivity analysis and for generating risk rankings after each round of weighting and the ensuing discussion.

3. Results

3.1. Results of Preference Elicitation by Rounds

Two rounds of weighting were completed on Day 1, with the third and final round completed on Day 2. Economic cost was the highest weighted criterion at a 25-26% range, while landscape amenity was weighted the lowest within a 10–12% range, based on mean weights of the 12 participants. In addition, the group as a whole did not change their preferences in any substantial manner with only minor differences in the weighting of the criteria among rounds (Fig. 4).

We used the SD of individual criteria weights as an indicator for group consensus. A decreased SD between rounds indicated consensus formation resulting from reduced variation in individual criteria weights. For example, if jury members were indeed learning from each other and adjusting their preferences in response to group deliberations between the first two weighting rounds, we would expect the SD to decrease. However, we did not observe any evident SD changes in round 2. Similarly, there was no obvious change when comparing the results of Round 2 and Round 3 weighting (Hurley et al., 2010).

However, in Round 3 we did notice an SD increase for the weights of economic cost assigned by a sub-group of participants who do not have a strong science background. For this group of nine people, the SD in Round 3 was 4.5 times greater as that in round 2. This jump in SD implied that the modeling-facilitated presentation and its following discussion on uncertainty did have an influence on this sub-group.

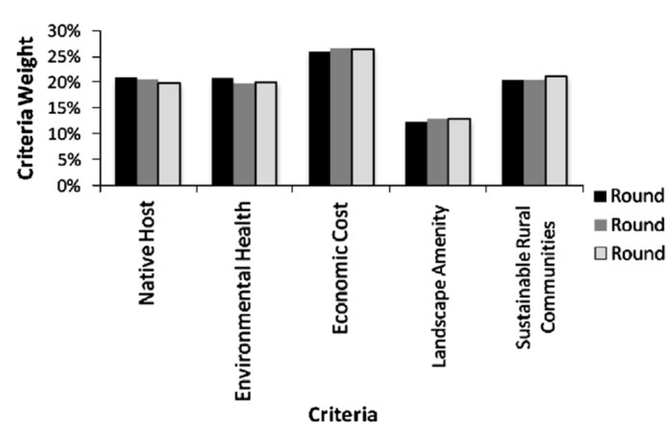

Fig. 4. Change in mean criteria weights by round (adapted from Hurley et al., 2010).

3.2. NIS Risk Ranking and Sensitivity Analysis

In the first and second weighting rounds, oriental fruit fly *(Bactrocera dorsalis)* had the highest overall risk rating, with no major changes in risk rankings between these two rounds (Hurley et al., 2010). The risk ranking for Round 3 (Fig. 5) remained unchanged, although the risk scores for some NIS were changed. This increase was mostly a result of the changes in impact scores (i.e. increased expected economic cost under the double-trouble scenario) rather than in the mean group weights. The oriental fruit fly was further confirmed to be of the highest risk due to a larger number for economic cost.

From Fig. 5, it is evident that the economic risk contributed to the majority of the high risk NIS, with the exception of apple maggot *(Rhagoletis pomonella)*. This is mainly a result of selection bias (Stanley, 2001, 2005). We included these ten species in our analysis because our stakeholders were more interested in the NIS with potentially high economic risks.

During the sensitivity analysis, the mean group weightings from Round 3 were substituted with the outliers for each criterion in order to assess potential ranking changes. The jury did not observe any major changes in the risk scores, which suggested the risk rankings (Fig. 5) were fairly robust to the changes in weighting.

4. Discussion

4.1. Possible Explanations for the Weighting Results

The deliberation process before round 2, in the form of structured discussion on those criteria for which weights differed most, did not change the group mean weights significantly. This might be attributable to several different factors. First of all, jurors' preference shift, if any, might have happened during the 'information phase' (before Round 1 weighting) rather than the 'deliberation phase (after Round 1 weighting)'. In other words, the participants had made up their minds after the expert testimony and its following discussion before Round 1 weighting happened. This result further confirmed the previous findings that the structured or formal deliberation process seems to matter less in changing people's mind, if it follows a combined information and unstructured group discussion phase (Goodin and Niemeyer, 2003; Liu et al., 2010).

Another possible explanation for no significant preference shift might be related to lack of interest. The project team noted that the jurors were fairly agreeable without major disagreements during the

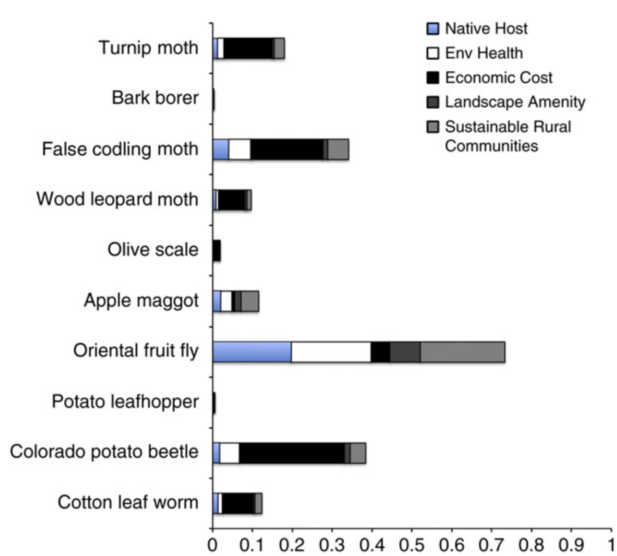

Fig. 5. NIS risk rankings based on round three weights and impact scores under the "double-trouble" scenario.

deliberation process. Because the NIS risk prioritization exercise was not tied to actual allocation in funding or immediate change in policy-making, it lacked personal relevance and may have accentuated consensus forming by removing incentives to confront the preferences of the outlying group members. In other contingent valuation casess, such as Ajzen et al. (1996) for example, authors have described how respondents are more likely to carefully process information relating to a choice when that information is of personal relevance. If it is not respondents may lack sufficient motivation to carefully consider it. This, in turn, signifies that respondents may base their final judgment on factors such as altruistic motives rather than self interest (Howley et al., 2010).

For the sub-group of nine jurors without a strong science background, the presentation and discussion on uncertainty after Round 2 weighting did seem to motivate them to process information more adequately. This was reflected by the dramatic increase of the SD assigned by the sub-group in Round 3. One possible explanation for the jump is that uncertainty was not naturally assumed for this sub-group of managers and growers before the uncertainty was explicitly reported and discussed.

Of course, due to the small sample size of our study this impact of uncertainty on less scientifically trained jury members requires further testing. But if it is proved true, it suggests that uncertainty is a barrier for consensus building in the context of risk management and special efforts are required in searching for the most effective way to communicate uncertainty (Dieckmann et al., 2009; Keller et al., 2009; Visschers et al., 2009; Wardekker et al., 2008).

4.2. Contribution of the Integrated Approach

The high level of uncertainties associated with NIS risk can be explained by the fact that the limited amount of data that we collect is not reliably representative of what has occurred (Franklin et al., 2008). This under-representation is due to the fact that only a small proportion of NIS spread and cause harm (Mack et al., 2000) and biological invasions frequently involve novelty (Williamson, 1999). Yet, numerous studies have shown that the impacts of this small group of NIS could be tremendous and irreversible (Millennium Ecosystem Assessment, 2005; Pimentel et al., 2005).

Because of these characteristics of low-probability, high novelty and high consequences, we believe the conventional risk assessment is limited in providing guidance in NIS risk management. The conventional model treats low-likelihood and high-impact risks in the same way as high-probability and low-consequence events in spite of the fact that the two types of risks are not likely to be viewed and managed in the same way (Bier et al., 1999). The integrated approach that we have demonstrated in this paper offers an innovative decision-aid, so that the special characteristics of the NIS risk are not camouflaged by expected value calculations of the conventional model.

When confronted with a complex decision-making problem, decision-makers tend to simplify the problem (Hey et al., 2010). The ecological economic model unpacks the complexity of the dynamics of the socio-ecological system of biological invasion in estimating economic risks. The model-facilitated scenario analysis empowers decision-makers to explore the effects of change in modeling inputs, including parameter values and underlying assumptions, on the assessment of NIS cost. Designed as a communication tool for the DMCE environment, the Stella model enables the uncertainty to be presented in an interactive manner.

Invasive species simultaneously generate multiple impacts on different social sectors, therefore, there are usually *economic, social*, and *environmental* dimensions of NIS risk to consider (Larson et al., 2011). These dimensions are not necessarily commensurable with each other. The DMCE provides a structured analytical approach to identifying stakeholders' key concerns and explicitly and openly addressing the economic, social and environmental dimensions of NIS risk. The sensitivity analysis of DMCE encourages decision-makers to explore different risk rankings with different impact scores and criteria weightings. This process of social learning is essential for robust decision-making (Kowalski et al., 2009). Linguistic uncertainty, the uncertainty component arising from under-specific, ambiguous, and vague use of our natural language, which is often ignored in decision-making analysis (Regan et al., 2002; Webb and Raffaelli, 2008), can also be eliminated or minimized as during the process of deliberation (Liu et al., 2010).

5. Conclusion and Future Directons

NIS risk management decisions must be made in the face of profound uncertainty (Maguire, 2004), so the issue for uncertainty is not how to avoid it, but how to account for it, and present it effectively to decision makers. In managing NIS, it is increasingly clear that a quantitative and expert view may be different from that of the public (Waage and Mumford, 2008) and a conventional model of risk assessment is limited in providing decision-support to manage the NIS risk with low probability, high novelty and high consequences.

With the high level of uncertainties in estimating both the likelihood and consequences, risks such as those imposed by NIS should be assessed by scenario analysis and a deliberative process (British Government's Parliamentary Office of Science and Technology, 2004). We integrated the two processes by using a model-facilitated scenario analysis to communicate uncertainty to the DMCE participants. Although a combined dynamic modeling and participatory MCDA method had been previously applied in supporting environmental decision-making (Kowalski et al., 2009; Wolfslehner and Seidl, 2010), to our knowledge, the integrated method reported in this paper is the first such operational tool in the context of risk management. In this paper, we have focused on the application of the approach for managing of NIS risk, but the same technique can be used in other contexts of environmental decision making, particularly when related to those risks of low-probability, high novelty, and high impacts (e.g. earthquake, infectious diseases, and abandoned hazardous waste dump).

Our case study demonstrates that such an integrated approach provides a promising tool for facilitating decision-making in the face of high uncertainty. The ecological economic model offers a systematic way of organizing data and synthesizing knowledge. The DMCE allows a participatory decision-making process with active involvement and commitment from the participants. The integration of the two processes provides a better understanding of system complexity and functions as a unique platform for risk communication. The participants of the final DMCE workshops were unanimous in their view that the integrated process added rigor into their thinking by presenting uncertainty explicitly and by providing an analytical basis around which they could focus their discussions.

Despite the positive feedback provided by the paricipants, we wish to emphasize the outcomes of our project are possible starting points for decisions in the policy arena of NIS prioritization, but not decisions per se. The second stage of the project is now ongoing with a focus on communicating uncertainty in the decision-making process of NIS risk management. This ongoing work attempts to provide mechanisms to more actively engage decision makers in understanding the potential risks of biological invasion. We plan to use both narrative means (e.g. images and stories for the less quantifiable risks of social and environmental dimensions) and numerical methods (a spatially explicit model to assess the economic risk) to lend visibility to the low-probability and high consequence risk. Furthermore, we are also interested in further exploring the influence of scientific uncertainty on decision-makers. For instance, if uncertainty is confirmed to be a barrier for forming consensus in the DMCE, it will be interesting to test whether deliberation can minimize or mitigate such a negative impact by offering an opportunity for structured discussion between decision-makers with different knowledge levels.

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