Biol Invasions (2011) 13:2323–2337
DOI 10.1007/s10530-011-0045-4

ORIGINAL PAPER

Incorporating uncertainty and social values in managing invasive alien species: a deliberative multi-criteria evaluation approach

Shuang Liu · Andy Sheppard · Darren Kriticos · David Cook

Received: 6 February 2011 / Accepted: 24 June 2011 / Published online: 9 August 2011

Abstract The management of Invasive Alien Species (IAS) is stymied by complex social values and severe levels of uncertainty. However, these two challenges are often hidden in the conventional model of management by "value-free" analyses and probability-based estimates of risk. As a result, diverse social values and wide margins of error in risk assessment carry zero weights in the decision-making process, leaving IAS risk decisions to be made in the wake of political pressure and the crisis atmosphere of incursion. We propose to use a Deliberative Multi-Criteria Evaluation (DMCE) to incorporate multiple social values and profound uncertainty into decision-making processes. The DMCE process combines the advantages of conventional multi-criteria decision analysis methods with the benefits of stakeholder participation to provide an analytical structure to assess complex multi-dimensional objectives. It, therefore, offers an opportunity for diverse views to enter the decision-making process, and for the negotiation of consensus positions. The DMCE process can also function as a platform for risk communication in which scientists, stakeholders, and decision-makers can interact and discuss the uncertainty associated with biological invasions. We examine two case studies that demonstrate how DMCE provides scientific rigor and transparency in the decision-making process of invasion risk management. The first case regards pre-border priority ranking for potential invasive species and the second relates to selecting the most desirable policy option for managing a post-border invader.

Keywords Non-indigenous species (NIS) · Biosecurity · Multiple impacts · Risk analysis · Participatory decision-making · Structured decision-making

S. Liu (✉) · A. Sheppard · D. Kriticos · D. Cook
CSIRO Ecosystem Sciences, Canberra GPO Box 1700, Canberra, ACT 2601, Australia
e-mail: Shuang.liu@csiro.au

S. Liu · D. Kriticos · D. Cook
Cooperative Research Centre for National Plant Biosecurity, Canberra, ACT, Australia

D. Cook
Fenner School of Environment and Society, The Australian National University, Acton, ACT, Australia

Introduction

Decision-makers face two major challenges when managing environmental risks (Gregory et al. 2006). First, risk management decisions frequently involve trade-offs between complex and often competing environmental, social and economic objectives with potential positive or negative consequences for different social groups. Second, understanding of these risks is often marked by profound uncertainties. When combined, these challenges too often become an excuse for maintaining the *status quo* instead of considering alternatives that might result in net social welfare gains.

The prevention and management of Invasive Alien Species (IAS) regularly confronts these two problems (Liu et al. 2010). The risks frequently concern multiple stakeholders, each with their own perspectives and priorities for preventing an undesirable species from establishing, and for managing its impacts once it has established. In addition, a high level of uncertainty prevails within each step of the invasion process, including how human actions can alter the process of invasion. Risk analysts faced with evaluating the risks of future invasions often have little information on the likelihood that a species will arrive, establish and spread in a new environment, and on the potential impacts should this occur. This is particularly true when the potential consequences of invasion are of a long-term and large-scale nature (Strayer 2009; Strayer et al. 2006).

The high level of uncertainty is in part explained by the fact that the limited amount of data we collect about invasions is not reliably representative (Franklin et al. 2008). Two reasons may explain this problem of under-representation: (1) only a small proportion of IAS spread and cause harm (Mack et al. 2000), and (2) biological invasions frequently involve novelty (Williamson 1999). Yet, numerous studies have shown that the impacts of this small group of IAS could be irreversible and tremendous (e.g. Pimentel et al. 2005; Millennium Ecosystem Assessment 2005).

Due to these low-likelihood, high-novelty and high-impact characteristics, it has been argued that IAS risks are difficult to handle within a conventional risk management framework (Horan et al. 2002; Simberloff 2005). In this paper, we argue that the conventional model has limited use in managing IAS risk for at least two reasons. Separation of risk assessment and management disrupts essential connections between the social values at stake in risk management and the scientific research involved in gauging the likely impacts of management actions, leaving the risk management decisions to be made in the wake of political pressures that reflect competing views on the proper tradeoffs among competing values (Maguire 2004). Furthermore, the pervasive uncertainty associated with the scientific analysis tends to be insufficiently communicated (Valle et al. 2009). This lack of communication may result in overconfident decisions at one extreme; at the other extreme, it could lead to a crisis-driven or "fire-fighting" approach (Shea et al. 2002) to IAS risk management, characterized by inaction before incursion happens, and potentially damaging over-reaction when incursion does occur (Sunstein and Zeckhauser 2008).

One new decision-aid tool that overcomes the two limitations of the conventional model by taking into account social values and uncertainty is Deliberative Multi-Criteria Evaluation (DMCE) (Fig. 1). DMCE seeks to combine the advantages of Multi-Criteria Decision Analysis (MCDA) in providing analytical structure to assess multi-dimensional objectives with

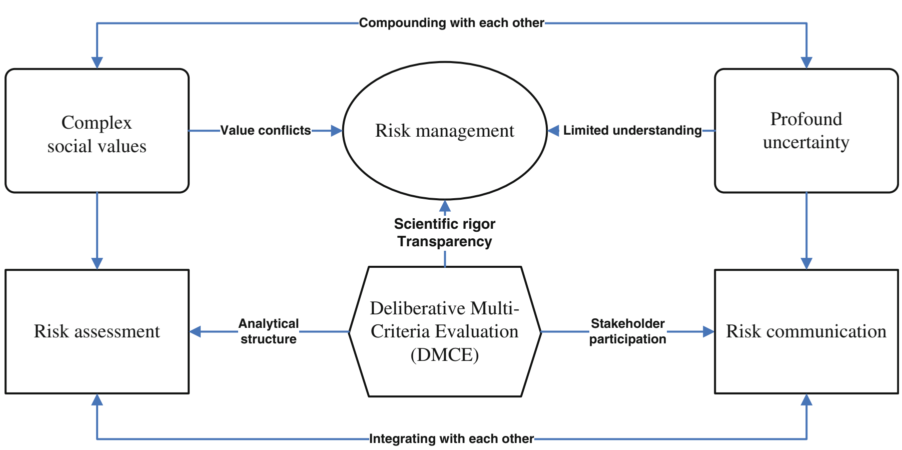

Fig. 1 Using DMCE to tackle the dual challenges of complex social values and profound uncertainty in managing biological invasions

the benefits of stakeholder participation (Proctor and Drechsler 2006). Compared to MCDA without a public involvement component, DMCE provides an opportunity for diverse stakeholder views to be explicitly incorporated within the decision-making process (Rauschmayer and Wittmer 2006). In addition, the DMCE can also function as a platform for risk communication, whereby scientists, stakeholders and decision-makers can interact and discuss the uncertainties associated with biological invasions. Thus, DMCE injects scientific rigor and transparency into the decision-making process of risk management by providing an analytical structure for social complexity and by integrating risk assessment and risk communication.

The DMCE method has been applied in the natural resource management arena as a decision-aid tool (Bojorquez-Tapia et al. 2005; Hajkowicz and Collins 2007), but it has only recently been used to assist IAS decision-making (Cook and Proctor 2007; Hurley et al. 2010; Liu et al. 2009; Liu et al. 2010; Liu et al. in press). In this paper, we situate our methodology within the risk management and science studies literature, addressing the limitations of the conventional decision-making model and proposing to use the DMCE as a new framework for managing the risks of biological invasion. We review the challenges of social complexity and profound uncertainty in IAS management and then later explain how DMCE can ameliorate, reduce, or even eliminate these factors.

Limitations of the conventional model of risk management in addressing social complexity and profound uncertainty

Risk assessment is the process of evaluating the probability of introduction and spread of an invader and the magnitude of the associated potential consequences (International Plant Protection Convention 2007). Conventionally, it is separated from risk management. The rationale for this separation is that the former is based in a realm of science and objectivity while the latter occupies a political realm where the subjectivity of social values and ideologies hold great influence. The two processes are also different in terms of their final outcomes. A risk assessment derives *risk*, a product of the likelihood of an event and its potential consequences. The goal of risk management, by comparison, is to identify *acceptable risk* (Fischhoff et al. 1981) and policy actions that manage these risks appropriately (Hummel et al. 2009).

This separation of risk assessment and management disrupts essential connections between the social values at stake in invasive risk management and the scientific research involved in predicting the likely impacts of management actions (Maguire 2004). As a result, risk assessment may fail to address stakeholders' major concerns because it is increasingly clear that a quantitative expert view may be different from the views of the public at large (Waage and Mumford 2008). In addition, the uncertainty associated with the scientific analysis could be ignored by, or insufficiently communicated to, the decision-makers, leaving risk management decisions to be made in the wake of political pressures that reflect competing views.

Uncertainty has many meanings and different disciplines have their own ways to classify and manage uncertainty (Bammer and Smithson 2008). For the purpose of this paper, we emphasize the classical difference between risk and uncertainty as proposed by Knight (1921). *Risk* designates situations when possible outcomes and their probabilities are both known (e.g. throwing a dice or tossing a coin). By contrast, *uncertainty* refers to situations when we only know the possible outcomes but not the probabilities of these outcomes. For example, successful NIS establishment is positively related to propagule pressure but quantification of the probability of establishment is still a challenge for most taxa (Kolar and Lodge 2001).

Risk and uncertainty are not synonymous. Yet, one of the hallmarks of risk assessment is the probability model, where uncertainty is treated as a state that can in principle be known through objective or subjective probability distributions. An implicit assumption for such probability-based models, whether it is a Bayesian net risk assessment or a cost benefit/effectiveness analysis, is that the quality of background knowledge is sufficiently high to justify such an approximation. However, this is often not true in the case of predicting unprecedented events such as climate change (Millner et al. 2010) and biological invasions (Gren 2008).

Indeed, while probability-based approaches are often an efficient method for studying simple and static systems, they are not considered adequate for complex socio-ecological systems with unforeseen or unknown future outcomes (Walker et al. 2002). The choice of treating a future event as either risky or uncertain largely depends on the novelty contained in the system (Brouwer and De Blois 2008). If the system contains little or no novelty, probability approaches may be sufficient. If the degree of novelty is excessive, however, probability approaches may not be sufficient to predict and manage future events.

We are often faced with a high level of novelty concerning invasive species, where uncertainty or even *ignorance* (when we do not even know the range of possible outcomes) is the norm (Horan et al. 2002; Williamson 1999). Even for the same species, there are many examples where it causes quite different impacts on ecosystem processes at different sites or at different times (Ehrenfeld 2010).

This uncertainty and ingorance, therefore, has to be accounted for and presented to those in charge of making policy decisions. A deliberation process has been proposed for such a purpose so that risk analysts, stakeholders, and decision-makers can all interact (Rodriguez-Labajos et al. 2009).

Analyzing complex social values in managing invasion risks with Deliberative Multi-Criteria Evaluation (DMCE)

An overview of the complex social values associated with biological invasion

The potential and actual impacts of biological invasions are many and varied. They may be *direct* or *indirect* (i.e. mediated through effects on other species or through an ecosystem) and may affect *market* (e.g. food, fuel, trade access) or *non-market* (e.g. ecosystem services, aesthetic enjoyment, and existence value of native species) goods and services of invaded systems (Colautti et al. 2006). Hence, there are usually *economic, social* (e.g. human health) and *environmental* dimensions of invasions to consider (Cook and Proctor 2007; Larson et al. 2011). It follows that invasive species simultaneously generate multiple impacts on different social sectors.

This multi-dimensionality is well expressed on the account of the black wattle (*Acacia mearnsii*) invasion in South Africa (de Wit et al. 2001). During the early stages, local farmers and foresters experienced economic benefits from this weed through access to cheap firewood. Subsequently, while the benefits continued to accrue, impoverished small landholders incurred economic costs through a loss of grazing potential once the invasion had taken hold. Another market impact the weed had on the local economy may be decreased income from tourism. There may be less expenditure on recreational activities if a landscape dominated by wattle is aesthetically less desirable due to habitat modification for large game. In terms of non-market impacts, the black wattle displaced certain native flora and fauna species and a proportion of the human population will suffer from *A. mearnsii* pollen allergies. Furthermore, the weed also had a detrimental effect on ecosystem services particularly in relation to catchment hydrology and nitrogen cycling.

Ideally, a risk management decision will succeed in balancing public benefits and undesirable costs to potentially affected parties, but in reality this may be difficult to achieve for potential IAS because the risks carry such a high degree of uncertainty. There can even be disagreement over the magnitude of likely impacts caused by the most high-profile invasions (Parker et al. 1999). Economic evaluations of biological invasions, for instance, tend to focus on direct or market impacts, while indirect and non-market impacts are often ignored or neglected because of difficulties in deriving appropriate estimates (Born et al. 2005). Even when such appropriate values are sought, an 'appropriate' value may vary depending on which stakeholder is consulted. Different stakeholders with different agendas and priorities among the competing objectives can perceive involuntary risks very differently (Simberloff et al. 2005). For example, a proposal to cultivate a potentially invasive weed for the production of biofuels will benefit the prospective farmers but concern ecologists (Davis et al. 2010; Meyerson 2008). From this perspective, environmental decision-making is akin to conflict analysis characterized by the ecological, economic and socio-political value judgments of different stakeholders (Munda et al. 1995; Martinez-Alier et al. 1998).

DMCE as a decision-aid to analyze complex social values

Decision scientists argue that good decision-making requires facts, values, and a process for their integration (Gregory et al. 2006; Renn 1999). To accommodate diverse value judgments, public involvement in environmental decision making has become a standard practice (Wilson 2008). In the area of environmental risk management, a hybrid analytical-deliberative process has emerged, of which DMCE is an example. The hybrid approach integrates quantitative risk assessment with participatory approaches that seek to incorporate a wide range of scientific expertise, local knowledge, and diverse values through a new form of science-citizen interaction (US National Research Council 1996; Renn 1999; Beierle 2002).

Several drivers are responsible for shaping this hybridized approach to risk management decision-making. First, participatory theory and deliberative democracy assert that individuals have a right to influence decisions that relate to their welfare (Dryzek 2000). Second, the integration of diverse social values into decision-making processes has multiple benefits, including increased acceptability and strengthened trust in risk decisions (Stirling 2006). Finally, risk assessment, which was believed to be completely objective, inevitably reflects tacit yet dominant cultural values and identities and is thus not a value-free process (Slovic 1999; Wynne 1992). The key question, is not whether subjective elements should still be considered in a decision-making process—they are part of it anyway; but how they should be articulated and incorporated via *a formal and structured analysis* (Keeney et al. 1993). With this in mind, decision support analysts need tools to integrate technical expertise, regulatory requirements, and public values. DMCE is one such tool: it allows structured decision-making by engaging multiple groups in a decision-oriented discourse that incorporates both facts and values (Liu et al. 2010).

The DMCE method combines the facilitation, interaction, and consensus-building features of citizens' jury processes with the structuring and integration features of traditional MCDA (Proctor and Drechsler 2006). It has been developed to encourage the more effective engagement of multiple stakeholders in the decision-making process as opposed to a single decision maker.

The citizens' jury involves around ten to twenty participants being charged with the responsibility of constituent representation and decision-making (Proctor and Drechsler 2006). The group is guided by an independent facilitator who ensures that participants have equal opportunity to express their views and that the process follows a course to achieve outcomes. The jury is encouraged to use expert witnesses, technical analyses, and anecdotal information to form individual opinions. Time is then devoted to information clarification and group discussion in which group opinions are voiced and modified using an interactive computer software package (e.g. MCAT/Multi-Criteria Analysis Tools, Marinoni et al. 2009). These modified group opinions sometimes indicate increased agreement among participants, which is potentially a very important feature of DMCE when used in a policy-making context (Webb and Raffaelli 2008; Redpath et al. 2004).

A detailed description of the DMCE process can be found in Proctor and Drechsler (2006), and is summarized in Fig. 2. The essential steps are as follows: First, a jury is selected, while ensuring fair representation of the various stakeholder groups. Next, the jury refines the overall goal of the DMCE procedure, the decision criteria, and the policy options to be considered. Experts then create an Impact Matrix (IM) to capture the estimated impacts of each the policy option relative to the individual criteria, against which each jury member assigns weights reflecting its relative importance. Once the criteria weights and IM have been determined, a deliberative process is carried out with the aid of the facilitator and interactive computer software. For each iteration, the software reveals to the participants individual and group preferences, thus providing a vehicle for negotiation and consensus building. Sensitivity analysis is used to demonstrate the effect of scientific uncertainty on the robustness of the rank order of different policy options as a final aid to the making of a consensus decision.

Communicating uncertainty in biological invasion decision-making with deliberative multi-criteria evaluation

Uncertainty in biological invasions

Biological invasions are notoriously difficult to predict (Williamson 1999). We currently have very limited knowledge regarding most species in terms of

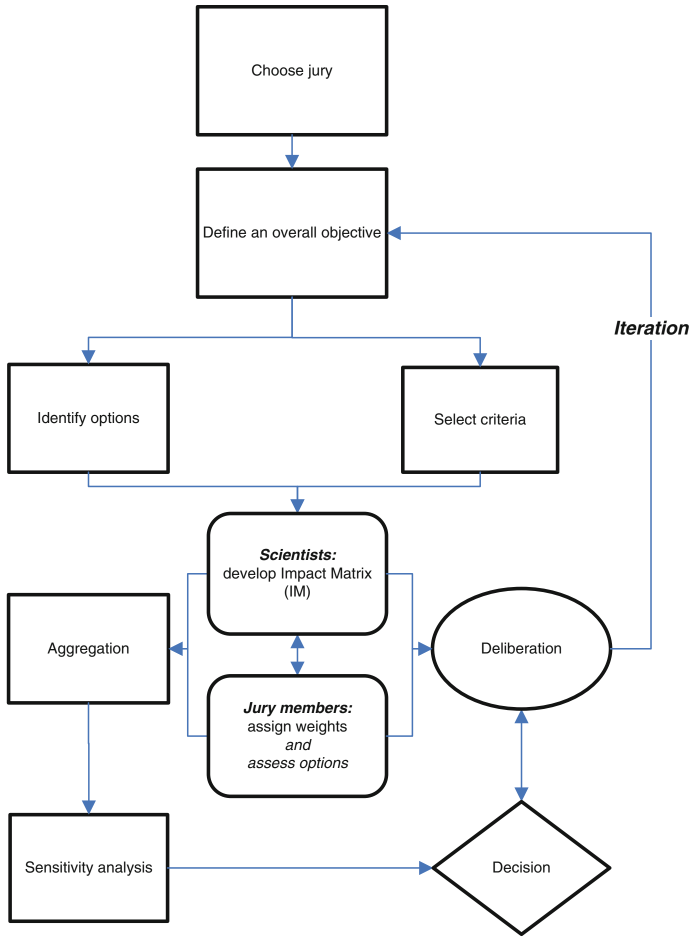

Fig. 2 Flowchart of DMCE procedure (adapted from Proctor and Drechsler 2006)

their establishment in a new environment and the impacts that it might cause (Simberloff 2006).

Although the work on identifying future invaders and predicting their likely sites of invasion are of immense scientific and practical interest, such efforts are often inconclusive (Mack et al. 2000). There are no universally reliable procedures for identifying the invasive potential of an organism. Stochastic effects and their spatial distribution co-determine whether a species becomes invasive (Pyšek and Richardson 2010). Hence, an IAS could remain innocuous in its new environment for decades or longer, then undergo a rapid population explosion to become a raging pest[1] (Groves 2006). On the other hand, occasionally populations of established IAS could undergo a spontaneous decline, sometimes all the way to local extinction (Simberloff and Gibbons 2004).

IAS impacts are also idiosyncratic and often unpredictable (Mack et al. 2000). The same species may cause quite different impacts on ecosystem processes at different sites or at different times (Ehrenfeld 2010). For an IAS that is established in a new environment, our ability to estimate its impacts in different dimensions also varies. Economic (e.g. on agriculture) and social (e.g. on health) impacts are relatively easy to assess and quantify because they are more easily perceived and are immediately reported by stakeholders (Vila et al. 2010). In contrast, the severe level of uncertainty in estimating environmental impact results from the long-term and large-scale nature (Strayer 2009; Strayer et al. 2006).

Biological invasion poses a serious challenge to risk analysts (Simberloff and Alexander 1998). Risk

[1] The phenomenon might be explained by ongoing propagule pressure, which aids an established IAS to spread by introducing genetic variation adaptive for new habitats (Simberloff 2009).

assessment of biological invasions requires consideration of the probability of each step in the invasion process, including entry, establishment, spread, and impact creation (Cook et al. 2007; Biosecurity Australia 2006). For many organisms, we know little of how to quantify these steps. Even in strictly controlled experimental conditions, endogenously generated variance in spread rate could be remarkably high, which indicates inherent limits to predictability (Melbourne and Hastings 2009). Therefore it is not difficult to understand why little effort has historically been aimed at quantifying biological invasions in risk assessment (Andersen et al. 2004; Bossenbroek et al. 2005). To date, most risk assessment protocols, such as the widely adopted weed risk assessment in Australia (Pheloung et al. 1999; Gordon et al. 2008), are based on expert opinion and qualitative assessment, and not on rigorous quantitative statistics.[2]

There is no doubt that great progress has been made on developing risk assessment for managing invasive species (Crowl et al. 2008; Pyšek and Richardson 2010). Due to data limitations, however, improved techniques *alone* will not necessarily enhance predictability. Only a small proportion of introduced species become invaders (Pyšek and Richardson 2010). The chance of an imported plant becoming a weed in Australia, for instance, ranges from 0.007 to 17%, with a central tendency of 2% (Smith et al. 1999). This low probability means there are relatively few data points with which to study biological invasions and any existing information may not be representative (Franklin et al. 2008). Additionally, most researchers work on invasive species with imminent or realized impacts because of funding availability (Pysek et al. 2008).

Prudent decision-making requires a tool explicit in regard to uncertainty and management options that are both precautionary and adaptive (Doak et al. 2008). Yet such a recommended strategy is hardly the norm in today's practice (Simberloff 2005). A common feature of many risk assessment models is that computation of risk probabilities are carried out *without* an uncertainty analysis (Benke et al. 2011). We believe the key to a solution is a new decision-making model that explicitly takes into account the uncertainty associated with the results of IAS risk assessment.

DMCE as a platform to communicate profound uncertainty

One of the most important explanations for the gap between science and policy is scientific uncertainty: scientists are familiar with uncertainty, yet the public and policymakers often accept scientific projections as certain (Bradshaw and Borchers 2000). A management decision that assumes risk assessment results are certain, when in fact they are not, can result in unexpected or undesirable outcomes (Peterson et al. 2003). In fact, the consideration of uncertainty may lead to a different decision in managing environmental risks (Burgman et al. 1999; Regan et al. 2005). Horan et al. (2002), for instance, argue that decision models based on standard economic theory have limited value when neither the range of potential impacts nor the possibility of these impacts is known for IAS management. They develop a model where policymakers cease maximizing their utility and became uncertainty-averse instead. As a result, it becomes optimal to devote more resources to confronting high-impact events even if the probability is considered low.

Environmental policy is believed to be most effective if scientific uncertainty is incorporated into a rigorous framework as reference for hypothesis building, experimentation, and decision making (Bradshaw and Borchers 2000). The frequently high level of uncertainty associated with biological invasions suggests that any quantitative model should be treated skeptically, and methods of communicating uncertainty should be applied (Franklin et al. 2008). DMCE is a method for reducing the discomfort with uncertainty for decision-makers and stakeholders.

An advantage of DMCE is that the deliberation process offers a unique opportunity for risk communication, the process that supplies lay people with the information they need to make informed, independent judgments about risks (Morgan et al. 1992). During deliberation, discussions can be geared towards what is known and what is not known, particularly the assumptions framing and embedded in the scientific knowledge of IAS risk assessment. Not only the quality of information built into the risk assessments is very important, but the ability of stakeholders and

[2] Quantative approaches for NIS risk assessment do exist (e.g. Kolar and Lodge 2002), but they are exceptions rather than a norm.

decision-makers to interpret and use this information is also critical (Gregory et al. 2006).

In addition to the uncertainty resulting from knowledge gaps (termed "epistemic uncertainty"), uncertainty also arises from under-specific, ambiguous, and vague use of our natural language (termed "linguistic uncertainty") (Regan et al. 2002). Though often overlooked in risk management, this latter type of uncertainty may be particularly pervasive in language-based settings where the same term is interpreted differently by participants, resulting in misunderstanding and arbitrary disagreement (Carey and Burgman 2008; Webb and Raffaelli 2008). One familiar example is the potentially confusing set of terms developed around biological invasions (Lodge et al. 2006) (e.g. exotic, alien, and invasive). Effective communication can prevent needless misunderstandings amongst jury members so that they can focus discourse on the most critical information concerning risk (Fischhoff 1995). The DMCE approach helps alleviate the negative impacts of linguistic uncertainty (Liu et al. 2010).

Case studies of applying the DMCE in managing IAS risks

Following Maguire (2004), we classify IAS risk management decisions into two categories: (1) decisions about potential IAS before they arrive in a certain country or region, and (2) decisions about response actions to IAS after they have arrived. In short, IAS risk management could be either pre-border or post-border. We provide a published case study for each of these situations (Cook and Proctor 2007; Liu et al. 2010). The focus of the pre-border study is the use of DMCE use as a decision-aid to analyze complex social values. The post-border study illustrates DMCE use as a platform to communicate uncertainty.

DMCE-facilitated decision-making on pre-border prioritization

The application of DMCE in IAS prioritization was first explored in a workshop in Perth, Western Australia (WA) in November 2005 (Cook and Proctor 2007). Decision-makers were asked to establish ten priority species with a wide variety of impacts, ranging from species that are predominantly of agricultural significance to those with substantial environmental or social implications. The decision-making group comprised representatives from government, industry, and community groups that might be affected in the event of an IAS incursion.

During the DMCE workshop, participants were asked to indicate the relative importance of each criterion in comparison to other criteria in a set (Fig. 3). They each distributed 100 points among the 10 criteria, and the same weighting process was carried out twice in total. Between the two rounds, the DMCE process involved asking participants to try to reach a consensus on criteria weights in an effort to reduce ranking variation and more clearly identify priority species. Those criteria for which weights differed most significantly were discussed first, with jury members who had expressed the most extreme maximum and minimum weights for each criterion asked to defend their choices. During this review process, jurors could reflect on their choices and those of other jury members and adjust their weights if they felt it was necessary. This revision process continued until participants were no longer willing to adjust their weightings.

Results of round-one weighting revealed that the criteria importance chosen by individual jurors differed considerably, particularly in relation to production costs, yield loss, human health, local economies, and extinctions and irreversibilities. Some disagreement over the criteria weights was resolved though deliberation, including likelihood of arrival, human health, local economies, extinction and ireversiblities. Although these changes were relatively minor, the discussion generated in the deliberation was revealing and informative to many of the jurors.

In round-two weighting, the prioritization results showed species of high environmental and social significance, such as guava rust (*Puccinia psidii*), which was absent from Australia, and red imported fire ant (*Solenopsis invicta*), which was present in only a small area, ranked higher than those of a predominately agricultural significance. At the time of the workshop, however, little importance was assigned to or funding allocated to either of these species in Australia. By comparison, better known pest species such as the Queensland fruit fly (*Bactrocera tryoni*) have traditionally attracted more attention, reflecting their potential high impact on

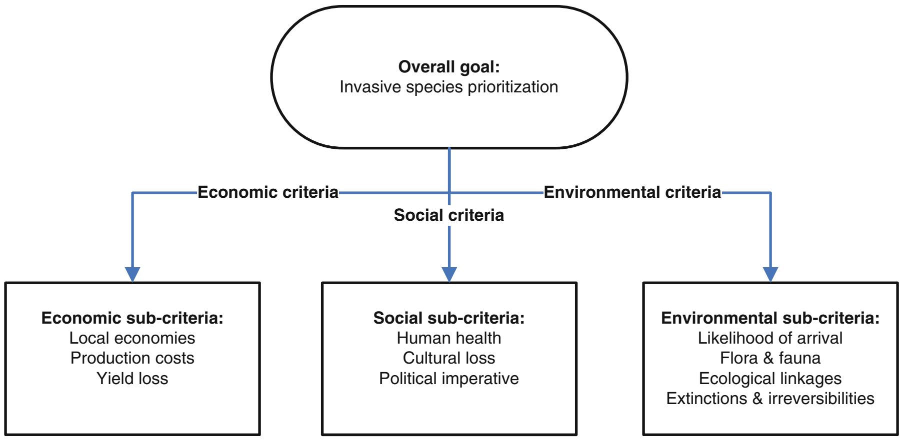

Fig. 3 The set of 10 criteria used in the pre-border DMCE study (Cook and Proctor 2007)

horticultural industries. This difference suggests that the way in which funds are allocated might need to be reconsidered.

In addition to the knowledge garnered regarding current methods of funding allocation, this trial case also demonstrated that much more time and effort is needed to negotiate some of the crucial trade-offs involved in certain management procedures, and that more detailed data relevant to the concerns of the decision makers be collected and for this information to be disseminated to participants in an understandable format and syntax. Further, it should provide for a truly iterative procedure as more information becomes available and more discussion and deliberation takes place. Ideally, the process would involve multiple months of workshops held at regular intervals. As a result of this trial study, the Australian corporate research centre of national plant biosecurity, Horticulture Australia Ltd., and the Rural Industrial Research and Development Corporation have initiated a joint project designed to further explore the role of DMCE in resource allocation decisions.

DMCE-facilitated decision-making in post-border response actions

There are few studies evaluating the risks associated with different management policies in response to invasions. Without this information policy-makers cannot make informed decisions on how best to manage incursions, which can lead to the IAS being given a lower priority than other concerns (Bossenbroek et al. 2005). To address this lack of information a DMCE was conducted with its overall goal of choosing one from among three regulatory actions to manage European House Borer (*Hylotrupes bajulus* Linnaeus) (Liu et al. 2010), 'one of the world's most destructive pests of seasoned softwood timber' (Australian Department of Agriculture 2005).

A high level of uncertainty exists in terms of how fast the *H. bajulus* could spread and whether the Borer is able to survive in roofing timbers in summer (ACG 2006). Following Regan et al. (2002), Liu et al. distinguished between epistemic and linguistic uncertainty (2010). In the *H*. bajulus case, Liu et al. (2010) *preserved* and explicitly accounted for epistemic uncertainty with a fuzzy set approach. At the same time, they attempted to *eliminate* linguistic uncertainty in order to ensure any change in preference was not the result of persons using words differently or inexactly.

Conventional (i.e. non-fuzzy) MCDA approaches typically assume that all information can be expressed as accurate values. This assumption is often not met in the real world where imprecise and vague information regarding our knowledge of the state of a system or human preferences in making trade-off decisions can only be represented qualitatively. Then in this case application of the fuzzy set approach is justified (Kahraman 2008). This approach can incorporate uncertainty in both the impact scores (i.e. value of each criterion for a particular management option, often provided by experts) and criteria weights (i.e. preferences about relative importance of each criterion, provided by stakeholders in a DMCE process), and in Liu et al's study (2010) the uncertainties in these two dimensions were explicitly addressed using the fuzzy set method.

In order to eliminate linguistic uncertainty the deliberation after the first round of weighting was dedicated to IM ratification. This experience revealed how divergence in preferences could be caused by factors other than preference differences *per se*. For example the jury realized that "doing-nothing" to "manage" EHB could mean either "leave it completely alone" or "eradication only, without forcing the industry to do any timber treatment". The differences in understanding towards this management option led to differences in the weights assigned to the sub-criteria of "administrative cost" in round one.

In total, three rounds of weighting were conducted to elicit both the jury's initial preferences and the preference changes that occurred after IM ratification and further deliberation rounds. Figure 4 shows the extent of weighting changes by round across the sub-criteria. These are expressed in percentage form and individual criteria are grouped together along the horizontal axis.

The IM ratification process between round one and two triggered changes in both IM and criteria weights, and the combined effect led to a change in the group's preference ranking of the three management options. Alterations to criteria weights between rounds two and three (Fig. 4) were obvious, but these changes alone were not sufficient to produce a shift in the ranking of management options.

If any conclusions can be drawn from the post-border study it is the critical role of linguistic uncertainty, or at least its potential of such, in IAS risk management. A change in a person's preference could then result simply from the difference in a person's understanding of the exact same terminology rather than an actual deep-seated ideological preference. Resolving linguistic disagreements is an important step, yet it has received little attention in the literature (Carey and Burgman 2008). As detailed herein, DMCE offers a great opportunity to detect and eliminate linguistic uncertainty via group discussion and social learning. At the same time the fuzzy-set approach may compound different types of uncertainties and introduce under-specificity, although it is more direct and intuitive compared to the probabilistic approach. How to communicate uncertainty effectively in the process of group decision-making warrants further investigation.

Discussion and conclusions

System-based approaches for managing risks pose a significant challenge. As Haimes reiterates, "to the extent that risk analysis is precise and simple, it is not real. To the extent that risk analysis is real and complex, it is not precise (Haimes 2009)". However, public officials and community stakeholders charged with the responsibility of making IAS risk management decisions on a regular basis do not necessarily

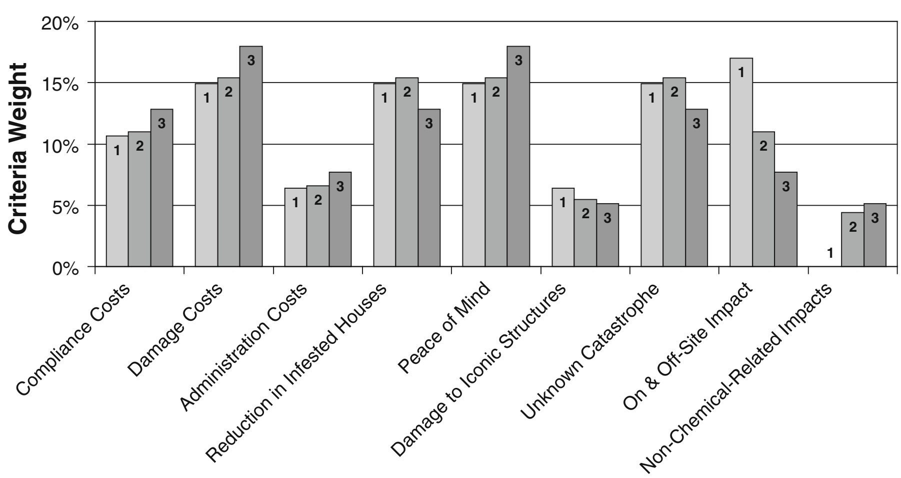

Fig. 4 Change in the jury's sub-criteria weights by round in the post-border DMCE study (Liu et al. 2010)

share this view. Even in the age of post-normal science (Funtowicz and Ravetz 1993), we often hear demands for "value-free" analyses and see probability-based estimates of incursion risk without sufficient discussion of true uncertainty. As a result, diverse social values are banished, and wide margins of error in risk assessment are neglected. This conventional model leaves IAS risk decisions to be made in the wake of political pressure and the crisis atmosphere of incursion (see Mackenzie and Larson 2010 for an example).

As a new decision-aid tool, DMCE injects scientific rigor and transparency in the decision-making process by providing an analytical structure for social complexity and by providing a platform for risk communication in which scientists, stakeholders and decision-makers can interact and discuss the uncertainty associated with biological invasions. It has been argued that people tend to rely on a limited number of "heuristic principles" to help them simplify the process of judgment (Kahneman and Knetsch 1992). Without the help of an analytical tool, decision-making tends to suffer from problems such as the omission of important criteria and fixed opinions based on insufficient information. Guided by the principles of multi-attribute utility theory (Keeney and Raiffa 1993), DMCE solves these problems by formally structuring a decision in terms of multiple criteria and policy options (Lahdelma et al. 2000; Gregory and Failing 2002; Failing et al. 2007; Gregory and Long 2009). The integration of risk assessment and risk communication has multiple benefits such as increasing the policy relevance of risk assessment, gathering more diverse and context-specific bodies of local knowledge from stakeholders, exposing and debating the conditional social assumptions embedded in the scientific knowledge (Stirling 2006), and providing an opportunity to proactively prepare the ground for policy changes (Penning-Rowsell et al. 2006). A decision based on such an integrated process will gain more public trust and credibility (Fischhoff 1995).

By no means do we wish to promote the DMCE technique as a panacea. There are a number of challenging issues to address when applying the DMCE in decision-facilitation for IAS risk. These include how a jury should be chosen, which can directly affect decision outcomes (Cook and Proctor 2007). It may be argued that information based on a DMCE should not be used as the only source of preference information because it will inevitably represent the voice of more active and opinionated jury members (Lahelma et al. 2000). In addition, a jury member unfamiliar with the deliberative process may encounter difficulty in participating and interacting with experts (Renn 2003), while a jury member familiar with the process may be prone to strategic misrepresentation of preferences. As in the case of valuation exercises in environmental economics, the DMCE process is also subject to the perils of information bias and "groupthink" (Ajzen et al. 1996; Janis 1982). Recent progress in psychological and behavioral research can shed light on solving these issues (Carlsson 2010; Kerr and Tindale 2004). Lastly stakeholder involvement requires investment in extra time, but this may not always be feasible during a crisis atmosphere of incursions and there is a need to develop rapid participatory methods (Mackenzie and Larson 2010).

We do not suggest nor intend to replace technical tools such as risk assessment and cost-benefit analysis with DMCE. On the contrary, we believe these tools could be integrated into a DMCE framework. For example, a cost-benefit-ratio may be used as one of the criteria regarding the desirability of different policy options for IAS management. We do argue that technical tools, though powerful, cannot *solely* solve environmental problems because environmental decisions are "political" as well as scientific and resolving environmental problems requires addressing the values of the public (Beierle 2002; Sarewitz 2004). We believe this statement is particularly true when there is profound uncertainty in our scientific understanding. "What to do in the face of uncertainty is a policy question, not a scientific question (Goldston 2008)".

Under this new model of DMCE-facilitated NIS risk management, scholars of biological invasion and risk analysts take the role of integrating their research results into the decision-making process. They fulfill this role by providing expert testimony to the DMCE process and by communicating not only their research but also the uncertainty associated with their results to the decision-makers. Essentially, this new decision-making model fits into a more democratic paradigm that conceptualizes scientists as part of society, working with others to solve problems together (Norton 1998; Larson 2007; Robertson and

Hull 2003; Pielke 2007). At the same time, the DMCE offers scientists an interactive platform where their work will be critically discussed and clearly interpreted to the end-users.

We put forward DMCE as a promising model for managing risks in the face of complex social values and profound uncertainty. In this paper, we have focused primarily on the uses of DMCE for the risk management of biological invasions. But the same technique can be used in other environmental risk management decision-making contexts, particularly when those risks have low probability, high novelty, and high impacts (e.g. flood, earthquake, infectious diseases, and abandoned hazardous waste dump). Applied over time, we believe this methodology will be able to trigger active adaptive management because it offers an opportunity for deliberative and transparent decision-making based on social learning (Cook et al. 2010; Penning-Rowsell et al. 2006; Shea et al. 2002).

Acknowledgments The authors would like to acknowledge the support of the Australian Cooperative Research Centre for National Plant Biosecurity, established and supported under the Australian Government's Cooperative Research Centres Program. We thank Paul De Barro, Terry Walshe, David Stern and two anonymous referees for their helpful comments on the manuscript.

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