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Analysis

Using an integrated fuzzy set and deliberative multi-criteria evaluation approach to facilitate decision-making in invasive species management

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ABSTRACT

There are two issues at the core of invasive species risk management: on the one hand, decision-makers struggle to balance environmental goals against other often competing societal goals such as economic benefits and social welfare; on the other hand, uncertainty often prevails in understanding the invasion process and in communicating invasion risks to the stakeholders. In this paper, we describe how an integrated Deliberative Multi-Criteria Evaluation (DMCE) and fuzzy set approach can tackle these two issues in the analysis of alternative risk management strategies, using the example of European House Borer (EHB, *Hylotrupes bajulus* Linnaeus). DMCE offers a platform for stakeholders to interact and to make a trade-off decision between multiple goals based on social learning and deliberation. The fuzzy set approach, applied within a DMCE framework, explicitly incorporates the inherent uncertainty in estimating potential EHB impacts and in evaluating participants' subjective preferences. This integrated method, therefore, provides a promising approach for tackling the dual challenges of competing goals and uncertainty in the evaluation of invasive species risk management options.

1. Introduction

The environment is a site of conflict between competing interests and values and environmental decision-making is inherently conflict management characterized by ecological, economic and socio-political value judgments of different stakeholders (Munda et al., 1995; Martinez-Alier et al., 1998). Often multiple management alternatives have to be considered and evaluated against multiple criteria that represent the competing values. Without the help of an analytical tool, decision-making tends to suffer from problems such as omitting important criteria and fixing opinions based on insufficient information. Multi-Criteria Decision Analysis (MCDA) proposes an analytical approach to solving these problems (Lahdelma et al., 2000).

Deliberative Multi-Criteria Evaluation (DMCE) seeks to combine these advantages of MCDA in providing analytical structure together with the benefits of stakeholder participation (Proctor and Drechsler, 2006). Compared to MCDA without a participatory component, DMCE offers an opportunity for explicitly allowing diverse views to enter the process, for facilitating consensus-building and for initiating a dynamic process of social learning (Howarth and Wilson 2006; Rauschmayer and Wittmer, 2006). DMCE has been applied in the natural resource management arena as a decision-aid tool (Bojorquez-Tapia et al., 2005; Hajkowicz and Collins, 2007) and only recently have researchers used DMCE in Invasive Alien Species (IAS) risk management (Cook and Proctor, 2007).

Here, we present another application of the DMCE technique in facilitating decision-making related to invasive species risk. Instead of assessing and ranking potential threats of different exotic pests, this time the DMCE is used to choose among multiple policy actions for managing a single invasive insect recently detected in Western Australia (WA), European House Borer (EHB, *Hylotrupes bajulus* Linnaeus).

EHB is 'one of the world's most destructive pests of seasoned softwood timber (Australian Department of Agriculture, Fisheries and Forestry, 2005)'. It endangers the structural safety of houses because a severe level of infestation could cause roof collapse. Chemical treatments of softwood used for new houses can eliminate this risk in safety by stopping the pest from spreading to structural wood. However, it is unlikely that the house building industry and new house owners will take such an action voluntarily. Such treatment will cost money, yet infestation does not reflect on the workmanship of the builders and after the house is built, borer infestation may not occur for a long time (ACG, 2006). In addition, chemicals used in treating the wood could have negative environmental impacts.

Therefore, any government regulatory action designed for mitigating the potential impact of the EHB has to take into consideration these social, economic, and environmental values. To add another

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layer of complexity to the issue, a high level of uncertainty exists in terms of how fast the EHB could spread and even whether the Borer is able to survive in roofing timbers in WA's hot summer (ACG, 2006).

In this paper, we apply a fuzzy set approach in conjunction with Deliberative Multi-Criteria Evaluation to solve the dual challenges of uncertainty and conflicting management goals. The fuzzy set method is particularly powerful in handling uncertainty within a MCDA framework and it is the most commonly used MCDA method for water resource planning and management (Hajkowicz and Collins, 2007). Yet, to our knowledge, nothing has been done to apply the approach in addressing the IAS uncertainty or in combination with deliberative MCDA.

2. Background

2.1. Rationale of using an Integrated Fuzzy Set-DMCE Approach in Dealing with Uncertainty in IAS Management

Zadeh (1965) established fuzzy set theory. The theory is designed for modeling situations where conventional binary outcomes are not feasible. Instead, it assumes that different grades of truth exist between false or true and there is a gradual transition from one class to another. Hence, an item can have partial membership in both classes.

The conventional (i.e. non-fuzzy) MCDA approach typically assumes 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, and in this case application of the fuzzy set approach is justified (Kahraman, 2008). This approach has the capability to 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).

Bellman and Zadeh first introduced fuzzy sets into the MCDA field (1970). Due to its intuitive and computational ease of analysis, the fuzzy set approach has become one of the most common methods for dealing with uncertainty in multi-criteria decision analyses (Kangas and Kangas, 2004). Over time fuzzy MCDA has been applied in supporting environmental decision-making in a number of contexts, including waste management strategy (Bellehumeur et al., 1997; Chiou and Tzeng, 2002; Uricchio et al., 2004), water management (Munda, 1995; Bender and Simonovic, 2000; Mazari-Hiriart et al., 2006; Srdjevic and Medeiros, 2008; Wang et al., 2008a), and energy planning (Wang et al., 2008b). To this date fuzzy MCDA has not been applied in an IAS decision-making context.

Uncertainty is a pervasive feature of IAS management issues (Perrings, 2005; Caley et al., 2006; Touza et al., 2007). Components of uncertainty in existing analyses include arrival (Batabyal and Nijkamp, 2007), demography and dispersal (Buckley et al., 2005), and impacts of invasive species (Horan et al., 2002). These uncertainty features are likely to become more prominent in the future in association with a wider range of global changes. Indeed, a major uncertainty in assessing patterns of invasion will be in predicting the "time bombs" or sudden non-linearity of invasions that occur in the context of global environmental change (Naylor, 2000).

Uncertainty has many meanings and different disciplines have their own in classifying and managing uncertainty (Bammer and Smithson, 2008). Following Regan et al. (2002), we distinguish between epistemic and linguistic uncertainty. The former is a reflection of incomplete knowledge, which includes uncertainty due to limitations of measurement devices, insufficient data, extrapolations and interpolations, and variability over time or space. The latter, on the other hand, arises from under-specific, ambiguous, and vague use of our natural language.

While there are more and more voices calling for adequate treatment of uncertainty in environmental decision-making in an explicit manner (Halpern et al., 2006; Georgiou, 2008), most studies have mostly focused on epistemic uncertainty and only a few researchers have taken an integrated approach to acknowledge and cope with both epistemic and linguistic uncertainty simultaneously (Regan et al., 2002). This is what we attempt to achieve with the fuzzy DMCE approach. We *preserve* and explicitly take into account epistemic uncertainty with a fuzzy set approach. At the same time, we attempt to *eliminate* linguistic uncertainty, to ensure any change in preference is not the result from people using words differently or inexactly.

2.2. European House Borer Incursion in Western Australia and Policy Reactions

The EHB was discovered on the outskirts of Perth, WA in January 2004 and as of August 2009 there were 152 confirmed findings in the Perth metropolitan area and more than 50 WA suburbs (Western Australian Department of Agriculture and Food, 2009). The Borer is a destructive IAS of seasoned coniferous timber, and is therefore capable of causing structural damage to buildings.

A national cost-shared control program commenced in January 2007. The Commonwealth (Australian Federal) government paid 50% of the costs of eradication and the remainder was funded by the WA State government. To supplement this eradication campaign, the WA Department of Housing and Works (DHW) commissioned a report investigating possible regulatory actions that could be taken to mitigate the impacts of the Borer on the housing industry. This report was intended to stimulate public consultation on possible regulatory options, and the three management alternatives the report proposed are as follows (ACG, 2006):

(a) Do nothing

There will be no additional building regulations put in place to guard against possible EHB damage.

(b) Statewide Building Restrictions

Regulations would be put in place banning the use of untreated structural softwoods in all new homes and businesses to ensure houses are structurally protected from EHB infestation.

(c) Delimited Building Restrictions

The use of untreated softwood building materials will only be restricted in areas where the Borer has been detected. This alternative relies on the assumption that EHB will not spread significantly beyond its current distribution.

3. Methods

3.1. Deliberative Multi-Criteria Evaluation (DMCE)

The methodology of this analysis was based on the DMCE procedure outlined in Proctor and Drechsler (2006). Compared to other MCDA approaches, DMCE is characterized by a public decision-making process involving a citizen's jury, which is based on the model used in English style criminal proceedings. Typically juries 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. Although desirable, this final outcome is not necessarily a consensus position (Cook and Proctor, 2007).

In a DMCE exercise, weights represent stakeholder preferences regarding the relative importance of each criterion, and a change in weight indicates a reflective shift of stakeholder preferences achieved through deliberation (Cook and Proctor, 2007). However, it can be argued that the change in preference is a result of both group deliberation and other factors (Hermans et al., 2008). We therefore included an extra round of weighting (round two) to minimize the possibility of the event in which preference changes in the last round of weighing (round 3) were due to factors other than deliberation. In particular, the jury ratified the Impact Matrix (IM) by examining it in great detail and by collectively assigning a new performance score if necessary (see the bolded cells in Tables 4b, 5b and 6b for the changes) before round 2 weighting. The impact matrix (Eqs. (1) and (2)) is a two by two table, each element of which represents the value for a particular management option (e.g. “do nothing”) according to a particular assessment criterion (e.g. “economic” or “social”).

The decision-making process benefited from this ratification process for at least four reasons. Firstly, it gave the jury ownership of the IM, which was mostly developed by the ACG report (2006). Participants reviewed each criterion through open discussion so that any information that was vague or left out could be considered. Secondly, this process eliminated linguistic uncertainties so that jury members shared a common understanding for the same term. Thirdly, it avoided the mistake of assigning criteria weights independent of impact scores. As a recent study showed, weights and performance score scales must be aligned if we want to properly elicit preferences (Steele et al., 2009). Lastly, this ratification process fosters social learning by presenting an opportunity for experts and stakeholders to interact.

After the second round of weighting, deliberation time was mostly spent on hearing from the jury members who assigned extreme weights at the second round (“outliers”), and on the following discussion on the merits of these outliers' rationale. Finally, the third round of weighting was carried out and we analyzed the data and presented the results to the jury. In the end, a group decision was made based on social learning and deliberation.

Fig. 1 illustrates the major steps of our DMCE exercise with an emphasis on the three rounds of criteria weightings.

3.2. Fuzzy Logic Methodology

In our study, the IAS management strategy performance evaluation problem involves a number (n) of discrete management options M_i ($i=1, 2, \ldots, n$). These options are to be scored according to a set of m criteria C_j ($j=1, 2, \ldots, m$), each of which is separated into p_j sub-criteria C_{ik} ($k=1, 2, \ldots, p_j$). Since some of the relevant criteria (i.e. those dealing with non-market IAS impacts) cannot be scored quantitatively, qualitative assessments are to be given according to a set of linguistic terms.

The linguistic terms defined in Tables 1 and 2 are used, each of which corresponds to a triangular fuzzy number representing their approximate value range between 1 and 9 (Juang and Lee, 1991; Yeh et al., 2000). The range is defined as (a_1, a_2, a_3), where $1 \le a_1$, $1 \le a_2 \le a_3 \le 9$. The values of a_1 and a_3 represent the lower and upper bounds of the fuzzy number, respectively, while a_2 is the most likely value of a linguistic term (Yeh et al., 2000).

The IM can be expressed as:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}. \tag{1}$$

Here, x_{ij} indicate the linguistic scores for IAS management option M_i ($i=1, 2, \ldots, n$) with respect to criterion C_j ($j=1, 2, \ldots, m$) (Yeh et al., 2000; Chang and Yeh, 2002). Since sub-criteria C_{ik} ($k=1, 2, \ldots, p_j$) are used for each criterion a more detailed IM can be expressed as:

$$Y_{C_j} = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{n1} \\ y_{12} & y_{22} & \cdots & y_{n2} \\ \cdots & \cdots & \cdots & \cdots \\ y_{1p_j} & y_{2p_j} & \cdots & y_{np_j} \end{bmatrix}, \tag{2}$$

where, y_{ik} are the stakeholder jury's linguistic scores for the performance of management option M_i ($i=1, 2, \ldots, n$) with respect to sub-criterion C_{ik} ($k=1, 2, \ldots, p_j$).

We use the fuzzy group multi-criteria decision-making approach described in Yeh et al. (2000) and Chang and Yeh (2002). A weighting vector W_j ($j=1, 2, \ldots, m$) for the perceived importance of sub-criteria to a decision-maker in making an IAS management decision is revealed using the linguistic terms in Table 2, and is expressed:

$$W_j = (w_{j1}, w_{j2}, \ldots, w_{jk}, \ldots w_{jp_j}). \tag{3}$$

Here, w_{jk} are the fuzzy weights for sub-criteria C_{ik} ($k=1, 2, \ldots, p_j$).

Sub-criteria weighting vectors were elicited individually for each jury member. By combining the score for each management alternative against each sub-criterion with the sub-criteria weights from one or more rounds of weighting by a stakeholder jury, each alternative can be ranked in order of preference to the jury. The widely used concept of the *degree of optimality* is used to establish clear and defined preferences. The optimal management alternative is the one that is both closest to the ideal solution and farthest from the negative ideal solution (Zeleny, 1982; Benıtez et al., 2007).

The first step in the ranking procedure involves the formation of a weighted fuzzy IM through the multiplication of the criteria IM Y_{C_j} (i.e. Eq. (2)) with a consensus weighting vector W_j (i.e. Eq. (3)); (Yeh et al.,

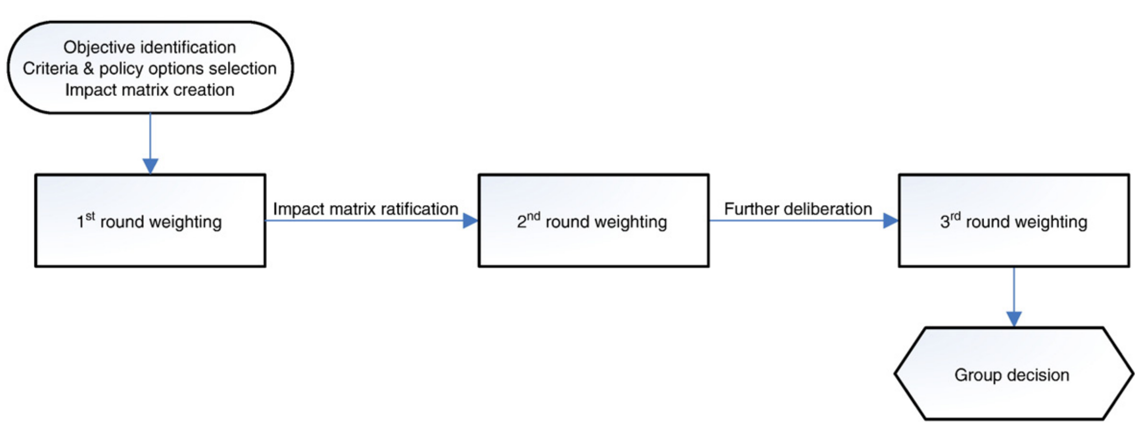

Fig. 1. The procedure of the DMCE process.

Table 1
Linguistic terms used to seed the impact matrix.
Adapted from Yeh et al. (2000).

Qualitative term	Very Poor (VP)	Poor (P)	Fair (F)	Good (G)	Very Good (VG)
Membership function (a_1, a_2, a_3)	(1, 1, 3)	(1, 3, 5)	(3, 5, 7)	(5, 7, 9)	(7, 9, 9)

2000). A normalized preference function $(x_{1j}, x_{2j},...,x_{nj})$ for criterion C_j with sub-criteria C_{ik} is given by:

$$(x_{1j}, x_{2j}, \ldots, x_{nj}) = \frac{W_j . Y_{C_j}}{\sum_{k=1}^{p_j} w_{jk}}. \tag{4}$$

From the scores and sub-criteria weights expressed by a stakeholder jury in $(x_{1j}, x_{2j},...,x_{nj})$, the IAS management alternatives with the maximum fuzzy preference value $(M^k_{\max})$ and the minimum fuzzy preference value $(M^k_{\min})$ with respect to each sub-criterion can be identified (Yager, 1980; Zadeh, 1998; Yeh et al., 2000). These represent the best possible (i.e. *supremum*, or least upper bound) performance rating and the worst possible (i.e. *inferium*, or greatest lower bound) performance rating of all alternatives with respect to each criterion C_j with sub-criteria C_{ik}, respectively, and their membership functions are defined as:

$$\mu_{M^k_{\max}}(x) = \begin{cases} \frac{x - x^k_{\min}}{x^k_{\max} - x^k_{\min}}, & x^k_{\min} \le x \le x^k_{\max} \\ 0, & \text{otherwise} \end{cases}, \tag{5}$$

$$\mu_{M^k_{\min}}(x) = \begin{cases} \frac{x^k_{\max} - x}{x^k_{\max} - x^k_{\min}}, & x^k_{\min} \le x \le x^k_{\max} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where $i = 1, 2, \ldots, n$; $k = 1, 2, \ldots, p_j$; $x^k_{\max} = \sup \bigcup_{k=1}^{p_j} (x_{ik}) x^k_{\min} = \inf \bigcup_{k=1}^{p_j} (x_{ik})$.

The degree to which any choice management option is desirable can be determined by comparing their normalized performance rating, x_{ij}, to $M^k_{\max}$ and $M^k_{\min}$. The difference between them, known as Hamming distances, are expressed as (Zadeh, 1998; Yeh and Chang, 2009):

$$h^+_{ik} = H(x_{ik}, M^k_{\max}) \tag{7}$$

$$h^-_{ik} = H(x_{ik}, M^k_{\min}) \tag{8}$$

For each sub-criterion C_{ik}, the Hamming distance h^+_{ik} measures the distance from the positive ideal solution, for which smaller values are preferred, while $\hbar_{ik}$ measures the distance from the negative ideal solution, for which larger values are preferred. Therefore, the greater the index of relative preference, given in Eq. (9), the more a management option M_i $(i = 1, 2, \ldots, n)$ is preferred by decision makers (Yeh et al., 2000):

$$P_{ik} = \frac{h^-_{ik}}{h^+_{ik} + h^-_{ik}}. \tag{9}$$

Table 2
Linguistic terms used to weight sub-criteria.
Adapted from Yeh et al. (2000).

Qualitative term	Least	Less	Fair	More	Most
Membership function (a_1, a_2, a_3)	(1, 1, 3)	(1, 3, 5)	(3, 5, 7)	(5, 7, 9)	(7, 9, 9)

4. Case Study

The objective of the DMCE study is to evaluate the three regulatory options (ACG, 2006) using a list of criteria developed in consultation with a citizen's jury, and to decide on the most desirable option according to these criteria.

The jury, totaling 10 people, was made up of representatives from local communities affected by or potentially affected by the EHB. Representatives from State government agencies involved in EHB management were also part of the jury, because the control of invasive species is a public good (Perrings et al., 2002) and this is particularly true for the Borer case, as no private party has an incentive to control the EHB.

These groups are detailed in Table 3.

Through investigation and consultation with different stakeholder groups potentially affected by EHB regulations for the building industry, three criteria (economic, social and environmental) were identified as being vital to a prioritization process incorporating a range of sub-criteria. These included three economic, four social and one environmental sub-criterion (Fig. 2).

4.1. Economic Criteria

(1) *Compliance costs (net present value over 100 years, 4.7% discount rate)*

These are the costs of adhering to the proposed regulations. Compliance costs will initially fall on home-builders as the costs of building materials will increase. These costs will ultimately be passed on to new home-buyers.

(2) *Expected damage costs (net present value over 100 years, 4.7% discount rate)*

The damage costs of infested houses given the continuation of current EHB monitoring and containment activities. People who own these houses over the decades to come will suffer from the expected damage.

Table 3
Jury composition.

Group	Description
Representatives from City of Wanneroo and Shire of Kalamunda	Local communities where EHB has been found. The councils of these local communities would be in a position to enforce any building regulations agreed to.
Representatives from City of Swan	Local community where EHB has not been found.
Department of Agriculture and Food - Western Australia (DAF-WA)	State government statutory agency that provides a range of services to WA's agricultural sector. DAF-WA is currently involved in the control and eradication of EHB.
State Department of Housing and Works (DHW)	State government agency that covers public and community housing, home loans and property sales. The DHW commissioned The Allen Consulting Group (ACG) report.

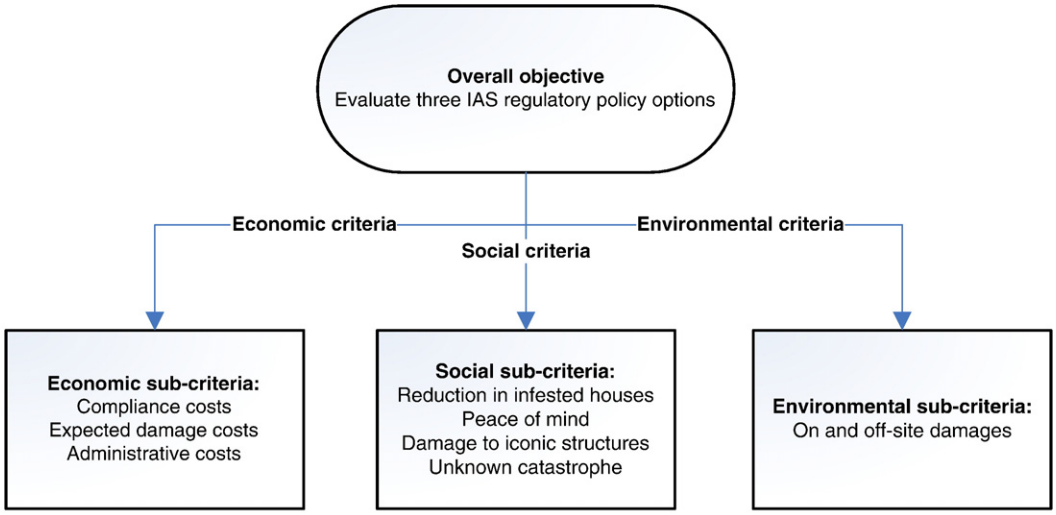

Fig. 2. Overview of objective, criteria and sub-criteria.

(3) *Administrative costs (net present value over 100 years, 4.7% discount rate)*

Administrative costs include items associated with the design and implementation of regulations. In the case of the proposed regulations, administrative costs will fall on the State government in terms of the initial implementation of the regulations and local government in terms of monitoring, enforcement and the assurance of compliance.

Table 4a shows quantitative data from the ACG report (2006) relevant to each of the economic criteria for round 1 weighting, and the corresponding score for each management alternative using the scale defined in Table 1. Table 4b presents the same set of information for rounds 2 and 3. During the process of ratification between rounds 1 and 2, the jury members updated the figures for administrative costs. They decided that the $47 million of eradication cost, which was included in round 1, should not be part of the administrative cost.

4.2. Social Criteria

(4) *Reduction in infested houses*

This sub-criterion viewed in a social context takes into consideration the health and safety aspects associated with EHB infestations. The regulations will protect the health and safety of: (i) occupiers of new houses and (ii) those working on new houses.It is difficult to accurately quantify the value of the health and safety benefits. However, the modeling undertaken by the DAF-WA indicates that the introduction of state wide building restrictions could decrease the number of infested houses from around 198,000 (over the course of 100 years) to 77 (Blanchard et al., 2005; ACG, 2006). Thus, the regulations could be seen to lower the risks of health and safety incidents occurring by a substantial degree.

(5) *Peace of mind*

The treatment of timbers to a level that would prevent EHB infestations may be a source of reassurance against attacks from other IAS. For instance, the treatments recommended for EHB also provide protection against termite infestations. This criterion captures the positive externality (or flow-on effect) from this additional protection.

(6) *Damage to iconic structures*

The structural quality and longevity of houses does pose significant public interest concerns, particularly as houses are significant cultural or personal assets. Modern churches, public buildings and works of art and other structures of social significance may also be put at risk by EHB infestation.

(7) *Unknown catastrophe*

This sub-criterion captures systemic risks brought about forces yet to be determined. The growing complexity of regulatory structures, corporations and institutions may make social systems less resilient to the impacts of a slow-spreading IAS like EHB in ways that are not yet depicted with the rest of the criteria, but which could impose a significant cost on future generations.

This criterion generated a fair amount of discussion and its definition and impact scores changed throughout the workshop (Tables 5a and 5b). In round 1, the jury decided that the existing criteria based on the ACG report (2006) failed to cover the long-term social impacts of EHB. For the next 100 years, the temporal scale of the AGC study, the impacts to the community will not be too large because of technological progress in pest detection. In addition, the

Table 4a
Quantitative assessment data and corresponding qualitative assessment results for the *Economic* Criterion for round 1 (VP: Very Poor, P: Poor, F: Fair, G: Good, VG: Very Good).

Sub-criterion	Management alternative		
	Do nothing	State-wide building restrictions	Delimited building restrictions
Compliance costs	0 VG	$697,000,000 VP	$35,000,000 F
Expected damage costs	$120,000,000 VP	$2,500,000 P	$3,500,000 P
Administration cost	$47,000,000 P	$47,052,000 VP	$47, 052,000 VP

Table 4b
Quantitative assessment data and corresponding qualitative assessment results for the *Economic* Criterion for rounds 2 and 3 (VP: Very Poor, P: Poor, F: Fair, G: Good, VG: Very Good; the bold indicated changes from round 1).

Sub-criterion	Management alternative		
	Do nothing	State-wide building restrictions	Delimited building restrictions
Compliance costs	0 VG	$697,000,000 VP	$37,000,000 F
Expected damage costs	$120,000,000 VP	$2,500,000 **F**	$3,500,000 **F**
Administration cost	**0** **VG**	**$52,000** **G**	**$52,000** **G**

Table 5a
Qualitative assessment results for the *Social* Criterion for round 1(VP: Very Poor, P: Poor, F: Fair, G: Good, VG: Very Good).

Sub-criterion	Management alternative		
	Do nothing	State-wide building restrictions	Delimited building restrictions
Reduction in infested houses	VP	VG	G
Peace of mind	VP	VG	G
Damage to iconic structures	VP	VG	P
Long-term impacts	VG	VG	VG

group agreed that there was no significant difference between the impact scores of the three policy alternatives.

In the later stages of the discussion, the jury shifted their focus to potential non-linear yet dramatic impacts posed by EHB to society by using the terms "intergenerational costs" (round 2) and "unknown catastrophe" (round 3). Though still struggling with defining the criteria in an unambiguous manner (see Keeney and Gregory, 2005 for a guideline on how to select criteria), they felt that "do nothing" would probably result in the "time bomb" of EHB impact to explode, especially in the context of global environmental change (Naylor, 2000), but the other two policy options would not mean much of difference in terms of social impact.

Tables 5a and 5b show the jury's scores for each management alternative using the scale defined in Table 1. During the ratification process after round one weighting, the members collectively changed some impact scores. In particular, they assigned "VG" to the criterion of damage to iconic structures for all three policy options, because one expert testified that buildings of social significance usually do not use the type of timbers with EHB infestation potential.

4.3. Environmental Criteria

(8) *On and off-site damage*

This criterion relates to chemical residue issues brought about through the increased use of insecticidal timber treatments. Chromated Copper-Arsenate (CCA), for instance, leaches out of the treated timber over time so there can be residues of arsenic, copper and chromium on the surfaces of the wood. Timber treatment plants can be particularly contaminated (i.e. referred to by the jury as *on-site* contamination). In addition, residues of arsenic, copper and chromium on the surfaces of the wood can be washed off by rain to accumulate beyond the confines of timber yards (i.e. referred to as *off-site* contamination of soil or groundwater).On and off-site environmental damage were treated as two criteria in round 1 but were combined in rounds 2 and 3. The jury also reckoned that chemical related impacts would be alleviated as less environmentally-fraught treatments are developed over time. Non-chemical-related environmental impacts of EHB infestation, including those related to house collapse and rebuilding, were included in the last two rounds of weighting. However, the jury did not think the impact scores of the three policy options would be significantly different.

Table 5b
Qualitative assessment results for the *Social* Criterion for rounds 2 and 3 (VP: Very Poor, P: Poor, F: Fair, G: Good, VG: Very Good; the bold indicated changes from round 1).

Sub-criterion	Management alternative		
	Do nothing	State-wide building restrictions	Delimited building restrictions
Reduction in infested houses	VP	VG	**VG**
Peace of mind	**P**	VG	G
Damage to iconic structures	**VG**	VG	**VG**
Intergenerational costs (round 2) or unknown catastrophe (round 3)	**VP**	**G**	**G**

Table 6a
Quantitative assessment results for the *Environmental* Criterion for round 1 (VP: Very Poor, P: Poor, F: Fair, G: Good, VG: Very Good).

Sub-criterion	Management alternative		
	Do nothing	State-wide building restrictions	Delimited building restrictions
On-site damage	VG	P	F
Off-site damage	VG	P	F

Tables 6a and 6b show the stakeholder jury's score for each management alternative using the scale defined in Table 1.

Three rounds of sub-criteria weighting were carried out and the sub-criteria weights given by the jury in each round are expressed using the terms described in Table 1. Using the responses contained in Tables 4a to 6b, Table 7 provides weighted fuzzy performance data (i.e. $W_j \cdot Y_{Cj}$) for each alternative management strategy in each round of weighting. The crisp performance index and rank derived from Eq. (9) is shown for each alternative in the final two rows of the table.

It is immediately apparent from Table 7 that the crisp performance index and the ranking of management alternatives change very little across the three rounds of weighting. However, the process of ratification between rounds one and two resulting in a change in both the impact scores and criteria weights appears to have been the most significant in defining the preferred course of management action. Preferences for the *statewide building restrictions* alternative were revised downwards in round two and remained the second (after the *delimited building restrictions* alternative) in round three. Alterations were certainly made to sub-criteria weightings between rounds two and three (Fig. 3), but these changes in weight alone were not sufficient to produce a change in the ranking of management options.

Fig. 3 shows the extent of weightings changes by round across the sub-criteria. These are expressed in percentage form, and individual criteria are grouped together along the horizontal axis.

5. Discussion

5.1. Treatment of Uncertainty

It is important to study the roles of uncertainty in decision-making because what we do not know could sometimes be far more relevant than what we do know (Taleb, 2007). In this study, we *preserve* and explicitly take into account the epistemic uncertainties in both impact scores and subjective preferences with a fuzzy set approach. At the same time we attempt to *eliminate* negative impacts of uncertainty to ensure any change in preference is not the result of linguistic uncertainty. The ratification process prior to the second round of weighting is

Table 6b
Quantitative assessment results for the *Environmental* Criterion for rounds 2 and 3 (VP: Very Poor, P: Poor, F: Fair, G: Good, VG: Very Good; the bold indicated changes from round 1).

Sub-criterion	Management alternative		
	Do nothing	State-wide building restrictions	Delimited building restrictions
On and off-site damage	VG	**F**	**G**
Non-chemical-related impacts	**F**	**F**	**F**

Table 7
Weighted fuzzy performance matrix, crisp performance index and management alternative rank.

		Round 1			Round 2			Round 3		
		Do nothing	State-wide building restrictions	Delimited building restrictions	Do nothing	State-wide building restrictions	Delimited building restrictions	Do nothing	State-wide building restrictions	Delimited building restrictions
Economic sub-criteria	Compliance costs	0.851	0.213	0.532	0.879	0.220	0.549	1.026	0.256	0.641
	Expected damage costs	0.298	0.447	0.447	0.308	0.769	0.769	0.359	0.897	0.897
	Administration costs	0.191	0.128	0.128	0.527	0.462	0.462	0.615	0.538	0.538
Social sub-criteria	Reduction in infested houses	0.298	1.191	1.043	0.308	1.231	1.231	0.256	1.026	1.026
	Peace of mind	0.298	1.191	1.043	0.462	1.231	1.077	0.538	1.436	1.256
	Damage to iconic structures	0.128	0.511	0.191	0.440	0.440	0.440	0.410	0.410	0.410
	Unknown catastrophe	1.191	1.191	1.191	0.308	1.077	1.077	0.256	0.897	0.897
Environmental sub-criteria	On-site impact	0.511	0.191	0.319	0.879	0.549	0.769	0.615	0.385	0.538
	Off-site impact	0.851	0.319	0.532	0.220	0.220	0.220	0.256	0.256	0.256
Crisp performance index		0.475	0.525	0.504	0.337	0.663	0.802	0.337	0.663	0.802
Rank		3	1	2	3	2	1	3	2	1

partially designed to mitigate the impact of linguistic uncertainty via group discussion and social learning.

The most common method in fuzzy MCDA is to use the fuzzy set approach to calculate both impact scores and criteria weights (Yuan et al., 2002; e.g. Chiou and Tzeng, 2002; Wang et al., 2008a). This is the method we adopt in this study.

For different components of epistemic uncertainties associated with impact scores, such as measurement error, systematic error and natural variation (Regan et al., 2002), the fuzzy set method simultaneously copes with them in an all-in-one manner. Compared to the probabilistic approach, it is also more direct and intuitive, which is important because simplicity and intuitiveness are critical for easy adoption of a decision support tool (Bender and Simonovic, 2000; Promentilla et al., 2008). On the other hand, the approach may compound different uncertainties and introduce under-specificity. To overcome this problem, we made an effort to ensure that all the available information was considered during the scoring process by providing a summary document of the EHB threat. In addition, the information in the IM was presented in both their natural units and fuzzified form.

In a DMCE process, a trade-off decision has to be made between the benefits of representing epistemic uncertainty in great detail and the cost of decreased comprehension. Although it is beyond the scope of this study to test how much exposure to uncertainty is optimal or the best way of presenting uncertainty, it warrants further investigation. Recent research showed, for instance, that people with different levels of numerical ability might evaluate risk forecasts in different ways, depending on how information is presented (Dieckmann et al., 2009).

In order to incorporate linguistic uncertainty (e.g. vagueness and ambiguity) in preferences, we asked the jury member to use a five-tiered fuzzy system (Table 2) for weighting. Although imperfect, this approach has the advantage of reducing stakeholders' cognitive burden in the evaluation process. Past research showed that ordinal ranking is a more favorable technique than other weighting methods (Hajkowicz et al., 2000).

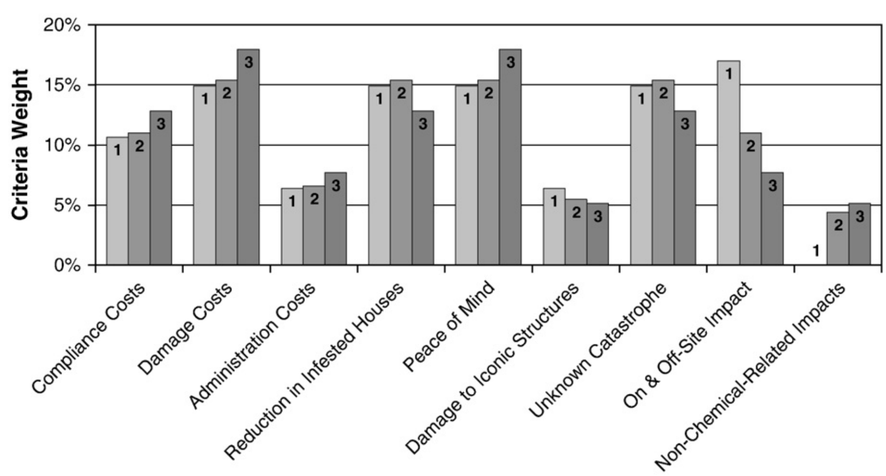

Fig. 3. Change in sub-criteria weights by round (note that the weights of the on-site and off-site criteria weights have been summed for round one).

One goal of DMCE is to reach greater consensus (Proctor and Drechsler, 2006). Yet a difficulty in group research is to link changes in preferences directly to deliberation or any single factor (Hermans et al., 2008). In our example, jury members' difference in round 1 criterion weights could be a result of preference differences *per se*, which we want to preserve, or other factors such as differences in understanding of the same term due to linguistic uncertainty, which we want to eliminate. We dedicated the discussion after the first round of weighting as an opportunity for impact matrix ratification. This experience revealed how divergence in preferences could be caused by factors other than preference differences *per se*. For instance, 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.

5.2. Treatment of Competing Goals

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). In a MCDA framework a decision issue often becomes clearer after it has been formalized in terms of multiple criteria and policy options (Hajkowicz, 2007; Failing et al., 2007). Decomposing the problem into more specific units can force people to consider all the aspects associated with a complex decision (Gregory and Failing, 2002; Gregory and Long, 2009). In the EHB case, this was accomplished by separating the three broad categories of criteria (economic, social and environmental) into eight specific sub-criteria and by presenting three policy alternatives.

Deliberative MCDA has become an increasingly popular area of research in recent years (Zografos and Howarth, 2008) and only recently has it been applied to risk management (Cook and Proctor, 2007). Compared to non-deliberative methods, the DMCE method offers at least two advantages. Firstly, it bridges the gap between risk assessment and risk management by encouraging a partnership between scientists and stakeholders. This paper has demonstrated DMCE as a flexible decision facilitation technique that provides a useful structural framework for making IAS management decisions. It provides a context for complex information to be communicated to diverse groups and trade-offs are transparent under this framework, adding accountability to the decision-making group. Secondly, it offers a research opportunity to explore social dimensions of risk. As observers for this deliberative process, it was obvious that risk was socially constructed (Slovic, 1987) and this was especially the case when scientific facts are not readily available. The inclusion of the criterion *unknown catastrophe* was a good example. In the face of uncertainty or even ignorance, how should a collective decision be made? Deliberative democracy is one answer to the question (Dryzek, 2000) and the DMCE approach provides a platform for diverse voices and preferences to be incorporated and interacted.

By no means do the authors wish to promote the DMCE technique as a panacea. There are at least three challenges in applying the DMCE in risk management. Firstly, deliberative processes pose new challenges to study the role of uncertainty. For instance, it is difficult to understand why a group's preference changes, whether it is due to new exposure to uncertainty and different formats of presenting the uncertain information, or due to other factors such as group dynamics and the group's education level. Secondly, the choice of a jury will no doubt directly affect decision outcomes (Cook and Proctor, 2007). Some argue that information based on a DMCE or participatory processes as such should not be used as the only source of preference information because it will inevitably represent the voice of the more active and opinionated population (Lahdelma et al., 2000). Thirdly, people are generally not familiar with the deliberative process. As a result they may encounter difficulty in participating. One comment from one of our DMCE participants was that he felt compelled to assign non-extreme weights because only group outliers were asked to speak. This happened despite constant reiteration from the facilitator that the purpose of DMCE was not uniform opinion. Overall, however, the feedback was positive. The jury felt that the process served to raise awareness, generate new ways of thinking, produce a solidly informed group, and to give the group a common language for future communication.

6. Conclusions

In this study we document how an integrated Deliberative Multi-Criteria Evaluation (DMCE) and fuzzy set approach can tackle the dual challenges of conflicting goals and uncertainty in the analysis of IAS risk management strategies. The goal for the DMCE is for the jury members to reveal their preferences and to come to greater consensus via social learning and deliberation. The fuzzy set approach is applied within the DMCE framework to take into consideration both the epistemic and linguistic uncertainties in the group decision-making process.

We designed three rounds of weighting in order to elicit both the jury's initial preferences and the preference changes that occurred after the ratification and further deliberation rounds. Our results show that the ratification process triggered change in both IM and criteria weights and the combined effect resulted in a group preference ranking for the three management options. Alterations were certainly made to criteria weights between rounds two and three, but these changes alone were not sufficient to produce a shift in the ranking of management options.

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