Eliciting and combining decision criteria using a limited palette of utility functions and uncertainty distributions: illustrated by application to Pest Risk Analysis

John Holt,[1,2]* Adrian W. Leach,[2] Gritta Schrader,[3] Françoise Petter,[4] Alan MacLeod,[5] Dirk Jan van der Gaag,[6] Richard H. A. Baker,[5] John D. Mumford[2]

[1]Natural Resources Institute, University of Greenwich, Chatham Maritime, Kent, ME4 4TB, UK

[2]Centre for Environmental Policy, Imperial College London, Silwood Park, Ascot SL5 7PY, UK.

[3]Julius Kühn Institute, Federal Research Centre for Cultivated Plants, Messeweg 11-12 38104, Braunschweig, Germany.

[4]European and Mediterranean Plant Protection Organisation, 21, boulevard Richard Lenoir, 75011 Paris, France.

[5]The Food and Environment Research Agency, Sand Hutton, York, YO41 1LZ, UK.

[6]Office for Risk Assessment and Research, Netherlands Food and Consumer Product Safety Authority, Utrecht, the Netherlands.

*Address correspondence to John Holt, Natural Resources Institute, University of Greenwich, Chatham Maritime, Kent, ME4 4TB, UK; tel: +44 1634 883225; j.holt@gre.ac.uk

ABSTRACT

Utility functions in the form of tables or matrices have often been used to combine discretely-rated decision-making criteria. Matrix elements are usually specified individually, so no one rule or principle can be easily stated for the utility function as a whole. A series of five matrices are presented which aggregate criteria two at a time using simple rules which express a varying degree of constraint of the lower rating over the higher. A further nine possible matrices were obtained by using a different rule either side of the main axis of the matrix to describe situations where the criteria have a differential influence on the outcome. Uncertainties in the criteria are represented by three alternative frequency distributions from which the assessors select the most appropriate. The output of the utility function is a distribution of rating frequencies that is dependent on the distributions of the input criteria. In Pest Risk Analysis (PRA), seven of these utility functions were required to mimic the logic by which assessors for the European and Mediterranean Plant Protection Organisation (EPPO) arrive at an overall rating of pest risk. The framework enables the development of PRAs which are consistent and easy to understand, criticise, compare and change. When tested in workshops, PRA practitioners thought that the approach accorded with both the logic and the level of resolution which they used in the risk assessments.

KEY WORDS: Risk matrix; Bayesian Network; Risk Assessment; Decision Making; Quarantine Plant Health

1. **INTRODUCTION**

Recognising that international trade can facilitate the spread of plant pests and other harmful organisms [1,2,3] the International Plant Protection Convention has developed standards within which contracting parties operate to mitigate phytosanitary risks without undue interference to international trade [4]. The primary international standard for pest risk analysis (PRA) is ISPM No. 11 [5]. While providing the structure and the elements to be included in a PRA, ISPM No. 11 does not itself provide a decision support system that enables the analyst to work through a logical series of questions for each pest or pathway of potential concern [6] or to incorporate the effects of uncertainty systematically [7]. To meet this requirement, regional [8] and national [9, 10] PRA schemes based on ISPM No. 11 have been developed which provide a framework for conducting PRAs which can then be used to support phytosanitary decisions.

The starting point for this work was the PRA scheme developed by the European and Mediterranean Plant Protection Organization (EPPO). The EPPO Decision Support Scheme (DSS) for PRA is based on a sequence of questions for deciding whether an organism has the characteristics of a quarantine pest and, if appropriate, identifies potential management options. The DSS consists of three stages: initiation, risk assessment and risk management [11, 12]. A computerised version of the DSS has been developed which facilitates the completion and recording of the analysis [13, 14]. There are approximately 50 questions within the risk assessment stage which is split between four main sections: entry, establishment, spread and impact/ consequences. Within each section analysts answer questions to ensure all key factors are taken into account and provide for an overall assessment at the end of each~~.~~ Three responses are required for each question: the selection of a likelihood or magnitude rating from a five point scale, the selection of an uncertainty score from a three point scale that reflects the confidence that the risk assessor(s) has in the rating they provide and a written justification for the rating and score selection supported, where possible, by literature, observations or other experience. At the end of each section, the analysts provide an overall summary rating and an associated level of uncertainty. The summary ratings act as reference scores for subsequent results derived from any prescribed combination of the ratings of the individual questions provided by a model. Analysts cross check summary ratings against model outputs and anomalies are investigated; rather than being a problem, such anomalies provide a useful pointer to those aspects of the specific assessment that may differ from a result based on general principles.

The EPPO DSS for PRA therefore requires pest risk analysts to define values for, and integrate, large numbers of qualitative or ordered criteria. Previously, the scheme asked questions about each risk criterion without a mechanism for combining risk and uncertainty and the objective of this work was to provide such a mechanism. Important considerations in the development of a suitable model were that:

1. The EPPO DSS is an established and widely used system in Europe and the objective was to improve its capabilities without radically altering the scheme.

2. The rating of the criteria and their interactions should achieve good consistency with the logic that assessors employ and the level of resolution with which they are able to express opinion
3. Uncertainties in criteria ratings should be expressed in such a way that they can be taken into account and compared consistently in the outcome of the assessment

Within this context, the objective of the paper is to describe a general modelling framework to integrate linguistically-defined ratings for decision criteria which have some degree of uncertainty and to illustrate this with the model developed for the EPPO DSS for PRA. It builds on the work carried out to develop and improve this scheme by two research projects, 'Prima phacie' (15, 16), and 'PRATIQUE' (17, 11). The former was directed towards the requirements of the European Food Safety Authority (EFSA) which differed in some respects from those of EPPO. Although there are some differences of detail, the underlying principles of the modelling framework discussed here are largely similar and apply to both.

2. METHOD

2.1. Model concepts

A modelling framework was developed which is an extension of a multi-attribute decision model of the type described by Bohanec [18] in his description of the decision-modelling software, 'DEXi', and its various applications [19, 20]. It is based on a hierarchical decomposition of the problem into sub-concepts and finally to a finite set of basic attributes which, in this application, are the questions in the PRA scheme. The rules for integrating the attributes are described by small sets of utility functions which are presented as tables or matrices which can be readily defined and scrutinised by PRA practitioners. They are an attempt at expressing the logic of how assessors integrate information. Matrices of various kinds are familiar tools in a number of PRA schemes [21, 10], as well as more generally in applications as diverse as highway construction project risk management, airport safety, homeland security and risk assessment of potential threats to office buildings [22]. Matrices of any dimension are possible but they quickly loose transparency if too many attributes are brought together at the same time; the structure is therefore restricted to a binary hierarchy, so that each utility function has only two inputs.

The approach extends that of DEXi by allowing (discrete) distributions of ratings to be used to describe the basic attributes. Thus rating uncertainty associated with the criteria is expressed as a frequency distribution. A small set of alternative frequency distributions are provided which correspond to the different degrees of uncertainty expressed by the PRA uncertainty score. The assessor selects visually that distribution which most closely represents their perception of the uncertainty.

Software developed for Bayesian Networks, Genie2 [23] provided a convenient platform that also offered graphical presentation. Although the model is essentially rule-based, the calculations are analogous to joint probabilities obtained in Bayesian Networks (BNs). The nodes linking the criteria are not conditional probability tables as used in a BN but are entirely deterministic, rule-based utility functions. The outputs of a utility function are the marginal frequencies from the joint rating frequency distribution of the two criteria, calculated according the particular utility function used.

The criteria or risk factors were described by a set of discrete categories or ratings which had linguistic definitions but which also had a definite order on a five-point scale. For example a particular risk factor might be described as: very low, low, moderate, high, very high. The linguistic definitions are frequently supplemented by notes and examples [24]. They are essentially relative or comparative in nature so that whilst it is not usually possible to give the rating a quantitative interpretation, they are consistent in that two pests with the same rating for a particular criterion should be broadly equivalent in this respect.

2.2. Implementation of the DSS for PRA

Rather than offering the risk analysts a completely open-ended choice of utility function a limited palette of five matrices are defined to describe the outcome of aggregating or combining criteria, two at a time. The outcome is described in the same linguistic terms as the original criteria, very low, low, etc. The five matrices are symmetrical about the main axis so that there is no differential weighting of the two criteria. The set of matrices offer the assessors a choice of rule by which to aggregate criteria into progressively more integrated concepts. They may select the smaller (minimum) the larger (maximum) or some intermediate: weighted towards the smaller (average, rounding down); the larger (average, rounding up); or to the more extreme, be it smaller or larger (average, rounding up if the average is greater than moderate and rounding down if less than moderate, described as 'rounding out'). The sequence: 'Minimum', 'Round-down', 'Round-out', 'Round-up', 'Maximum', can be considered to express a decreasing degree of constraint by the criterion with the lower rating over the other (Table I). At one extreme a Minimum matrix defines the outcome as the lower of the two ratings, so the lower value imposes a complete constraint over the higher. This expresses the idea of a necessary condition so that both criteria must achieve a particular rating in order for the outcome to reach that rating. At the other extreme a Maximum matrix defines the outcome as the higher of the two, so the lower rating is not a constraint on the outcome. This expresses the idea of a sufficient condition, so that if either criterion achieves a particular rating than the outcome also reaches that rating. For example:

Minimum (*very low*, *high*) = *very low*,　　　Maximum (*very low*, *high*) = *high*

The outcomes of the three other matrices give a value intermediate between the two criteria but vary in their rounding assumptions. For all three, the outcome is related to the intermediate of the two ratings but, being a discrete model, if this falls on the boundary between two categories the result is rounded up or down according to the matrix type. For example, the intermediate between very low and high lies between low and moderate, so two rounding assumptions are possible:

Round-down (*very low*, *high*) = *low*,   Round-up (*very low*, *high*) = *moderate*

The Intermediate round out matrix is a hybrid of these, rounding down where the intermediate value is less than moderate and round up where it is greater than moderate, for example:

Round-out (*very low*, *high*) = *low*,   Round-out (*low*, *very high*) = *high*

This set of five matrices can also be used to express differential weighting of the two criteria. By dividing the matrix along its main axis (top left to bottom right), a series of nine asymmetrical matrices can be obtained from pair-wise combinations of the original five (Table II). There are only nine non-trivial combinations because Minimum combined with Maximum yields a matrix in which one variable has no influence on the outcome.

The five symmetrical matrices together with three of the asymmetrical combinations are shown in Fig. 1. This set of matrices proved sufficient to provide a set of rules to mimic assessor logic in models for PRA. The rules defining the asymmetric matrices are a direct extension of the original five except that a different rule applies according to which variable is the larger; in the top right part of the matrix, the column variable is larger and in the lower left part, the row variable is the larger. The upper right triangle is defined by one rule and the lower left by another; the asymmetrical matrices therefore provide a set of utility functions that are conditional on the relative values of the inputs. For example in the Round-down/Minimum matrix, if the column variable is less than the row variable, the outcome is the minimum (i.e. equal to the column variable); if the column variable is greater than the row variable, the outcome is intermediate, rounded down. All the matrices considered here have the property that where two ratings are equal, the outcome is also that rating, so all rules deliver the same outcome for the five cells on the main axis, top left, to bottom right.

The matrices are deterministic, so if the ratings for the criteria are known the result is also known; the outcome is simply given at the appropriate row/column intersection in the matrix. In practice, the ratings could not usually be judged with such certainty and a consistent approach was required to express this. Following a similar 'limited palette' philosophy to the selection of the matrices themselves, a small set of rating distributions is defined from which the assessors choose the one closest to their perception of the uncertainty associated with the rating. The most likely rating is attributed the highest frequency and, following a distribution around the most likely, the other ratings are attributed to lower frequencies. The distribution is accordingly narrow to reflect low uncertainty and wider to reflect high uncertainty. The set of predefined distributions are based partly on Intergovernmental Panel on Climate Change (IPCC) definitions [(25)] and partly on Beta or truncated Normal distributions to complete the details of the distribution shape (Fig. 2); the choice of distribution type is not critical*;* the distribution patterns were slightly different but not sufficiently so for pest risk analysts to express a reasoned preference for one over the other. The Beta and Truncated Normal distributions were both convenient distributions for bounded variables [(26)].

With the rating expressed as a frequency distribution rather than a single value the calculation is more involved than simply finding the intersection of the correct row and column but the principle is the same. For each intersection, the frequency is calculated by multiplying the rating frequencies of the two criteria corresponding to that intersection. This gives the joint frequency distribution and by summing the cells falling in the different outcome categories defined by the matrix type, we obtain the frequency distribution of the outcome ratings. Fig. 3 illustrates how the distributions for crop impact and environmental impact are integrated using a maximum matrix. In this example, crop impact is moderate with moderate uncertainty and environmental impact is low with moderate uncertainty. The calculation proceeds as follows: to calculate the frequency of ‘low’ (16.6%) in the combined impact, we take the sum of the frequencies for the appropriate cells of the matrix (50% x 1%) + (50% x 24%) + (17% x 24%) = 16.6%. The procedure is the same for other matrix types except different groups of cells are summed as indicated by the shading/text in each matrix (e.g. Fig. 1).

3. RESULTS

It would be prohibitively long to describe the application of the framework to an entire PRA scheme so we illustrate the approach with a series of examples from the scheme. Full details of the entire PRA scheme can be found for a series of cases on the EPPO website [27].

With the exception of the Round Down matrix, those shown in Fig. 1 express the logic by which criteria are combined in the models for PRA. The remaining four symmetrical matrices were employed extensively within the model framework and examples of their use are shown in Fig. 4. In the matrix describing the movement of a pest along a pathway (Fig. 4 a), both the volume of shipment and the extent of pest association with the pathway should be taken into account so the result is a rating intermediate between these. Since particularly high or low ratings of either risk component are likely to skew the outcome, the Round-out matrix is used.

In the matrix summarising overall impact (Fig. 4 b), since the combined outcome may be due to impact on crops, the environment or both, a maximum matrix is appropriate.

Conversely, for conditions to be suitable for establishment (Fig. 4 c), both the climate and the abiotic conditions must be suitable, hence a minimum matrix is used.

In some cases, the choice of the matrix to be used is less clear. For example, the matrix shown in Fig. 4 d determines the extent to which establishment remains uninfluenced by crop or commodity management actions or ecological factors such as predation and competition. Since both factors are likely to influence rather than determine establishment, a Round-up matrix is considered to be most appropriate.

When first devised, the modelling framework used the set of five symmetrical matrices only and where some difference in weighting between inputs was judged necessary, an asymmetric matrix was defined element by element by considering all combinations of the input ratings and deciding in each case what the outcome should be. Subsequently, consistent rules for the asymmetric matrices were defined to bring them into accord with the original five. As might be expected, the new asymmetrical matrices differed but only slightly, from those devised element by element; the differences are shown for in Fig. 5.

In IPPC terminology 'introduction' is defined as '*entry of a pest resulting in its establishment'* [28] and the matrix determining Introduction integrates entry and establishment (Fig. 5 a). Introduction will only occur when entry occurs and the conditions are suitable for establishment. The suitability of the environment for establishment is considered somewhat more important than the number of entries (i.e. the likelihood of entry). This consideration is implemented in the utility function for combining entry and establishment as follows: if entry has the greater rating the result (the likelihood of introduction) therefore depends largely on establishment (equivalent to taking the minimum) and if establishment has the greater rating then the result depends on both but is weighted towards the lower (round down). Consequently a Round-down/Minimum matrix is appropriate. In the Round-down/Minimum matrix the outcome depends on establishment if entry has a higher rating than establishment but constrains establishment with an outcome intermediate between entry and establishment if entry has lower likelihood.

A utility function to provide a measure of overall risk would need to integrate the likelihood of introduction with the magnitude of the consequences (Fig. 5 b). Many analysts and policy makers do not find this final step helpful, preferring to keep the two aspects of the decision, likelihood and consequences, separate. It is therefore omitted from the models implemented in the EPPO Computer Assisted PRA scheme (CAPRA) but should some overall measure of risk be required in some circumstances, it was provided in the models developed for EFSA in the Prima phacie project [16]. The utility function is based on similar reasoning to the previous matrix in that the risk depends more on consequences unless introduction is limiting. If introduction has the higher rating, the result depends largely on consequences. If consequence has the greater rating then the result depends on both but more extreme values for consequences are considered to influence the result. Therefore, a Round-out/Minimum matrix is appropriate as the rounding out gives greater weight to consequences when its rating is particularly high.

A third asymmetric matrix, the Maximum/Round-up, is considered potentially appropriate to integrate the direct impact of the pest with any impacts caused by the exacerbation of other pests. The guidance notes for assessors using the EPPO PRA DSS state that *"if the response to the questions concerning direct impact are "major" or "massive" then evaluation of the other questions in this section may not be necessary."* The 'other question' in this case concerns the exacerbation of other pest problems. The Maximum/Round-up matrix expresses this conveniently by taking the rating for the direct impact if this is the higher and an intermediate rating, erring on the larger of the two, if non-direct effects are higher, so it only takes into account these effects if they are greater than the direct effect (Fig. 5 c).

In many decision model frameworks, including DEXi, there is a hierarchical structuring of a problem into sub-concepts and finally into a set of basic attributes which, in this case, have ratings elicited through the PRA scheme questions. The hierarchy expresses the dependency of events such as pest entry or pest establishment on a more detailed set of events or attributes. In the framework described here, the rating distributions provided a description of the basic attributes which also incorporated an expression of uncertainty. The matrices provided the utility functions to relate elements of the hierarchy to each other. The matrices are restricted to two dimensions and the criteria are combined within a binary hierarchy. Starting with the PRA scheme questions and the set of available matrices, PRA practitioners were able to construct hierarchies which reflected their logic in integrating the information to give an overall rating for entry, establishment, spread and impact of the pest. Examples of these hierarchies for entry, establishment and environmental impact can be found in Holt *et al.* [29], Schrader *et al.* [24] and Kenis *et al.* [30], respectively.

Illustrated here are the top level of the hierarchy employed in the EFSA model (Fig. 6) and the sub-model describing the pathways of entry (Fig. 7). Together, these employ five of the matrices from the set in Fig. 1. The top tier of the model employs two maximum matrices and two asymmetric matrices (Fig. 6) and the pathway sub-model, a round-out, a maximum and three minimum matrices. With the exception of the nodes, 'entry' and 'consequences moderated by lack of spread', the elements of Fig. 6 have already been explained in Figs. 4 and 5.

With multiple pathways (two are shown here), entry is defined by the maximum. It should be remembered that this is not simply the highest rated pathway but the frequency with which a particular rating is the highest across all pathways. For example in Fig. 3, in which the calculation is also based on a maximum matrix, the combined impact is 'high' with a frequency of 28% which is a higher frequency than that for the criteria individually.

The utility function, Round-out/Minimum, is used to define 'consequences moderated by lack of spread' and is the same as that used to describe overall pest risk (Fig. 5). In this case, if spread has the larger rating, the result depends on consequence. If a consequence has the higher rating then the result is affected by spread so consequence is moderated in cases when spread is low.

For the sub-model describing pathways of entry (Fig. 7), 'movement along the pathway' is discussed in Fig. 4. The extent of pest transport depends on which of the two processes, survival or increase (in prevalence), is the greater contributor to risk so the maximum utility function is used. The utility functions defining the extent to which the pest travels, arrives and finally enters along that pathway, all use the concept, minimum, because at each of these steps the result is constrained by which ever contributory risk factor is lowest.

The models described have been adopted as a component in the EPPO DSS (embedded into CAPRA software) [14] and scrutinised by several EPPO Expert Working Groups (EWGs), an EPPO\PRATIQUE workshop in Hammamet, Tunisia, in November 2010 [31] and by the EPPO Panel on PRA Development. Case studies of ten pests selected by EFSA offered opportunities for evaluation by other Pest risk analysts within the context of Prima phacie.

4. DISCUSSION

Pest risk analysts employ an underlying set of rules or principles in carrying out a PRA. These rules are often implicit or unformulated within the mind of the analyst and the approach discussed here is an attempt to make this process explicit. The model attempts to mimic the logic by which assessors combine ratings of individual criteria to arrive at overall ratings for pest entry, establishment, spread and impact. The utility functions employed here are not risk matrices in the usual usage of the term. A risk matrix has likelihood on one axis and impact on the other, the risk being the product of the two defined by the joint probability distribution. The logic employed by the assessors is not well represented by the use of product matrices. A particular illustration of this is that where two criteria are rated 'medium', the anticipated result is frequently also 'medium', whereas under a situation where the ratings represent the multiplication of underlying probabilities, the joint probability would be somewhat lower than the probabilities of the two inputs.

The utility functions or matrices are closer in concept to what have been described as ranked nodes in Bayesian networks: nodes which represent qualitative variables that are abstractions of some underlying continuous quantities [32]. A small number of nodes of this type were found to be sufficient to represent a variety of situations, e.g. software defects, air-traffic control and operational losses [33, 34, 35]. Fenton [32] distinguished four types of node: average, maximum, minimum and 'mixminmax', the latter being a mixture between minimum and maximum functions, and used weightings to achieve levels of gradation between them. In our experience in Pest Risk Analysis, similar basic node types: average (rounding up or ‘out’), minimum and maximum were found to be sufficient for most situations and the asymmetric matrices we also employed can be thought of as equivalent to using different weightings for the inputs or parent nodes. The major difference in the approach described here is that the nodes remain strictly deterministic.

Several earlier attempts to combine assessment criteria used averaging so *some form* of weighted average may be what is sought. However, an overall average is not appropriate [36] and the development here is that instead of combining everything with a notion that the result should be intermediate between the inputs, the criteria are combined step by step so allowing a wider range of logical relationships than just ‘intermediate’ to be applied. An intermediate value was simply not logical for many of the combinations and the design and selection of utility functions were the result of a thought processes to combine the criteria ratings more rationally.

The methods proposed in this paper accommodate the existing structure of an established scheme, the EPPO DSS for PRA which is strictly designed to follow all facets of ISPM 11 so is necessarily complex. The complexity and sophistication of the scheme does limit the range of feasible modelling approaches. Had there been the flexibility to create a new scheme from first principles, the choice of approach may have been wider but a new scheme might not have conformed to existing protocols nor have been readily adopted.

Approaches other than that presented here were considered over the course of the PRATIQUE and Prima phacie projects [11, 16]. The DEXi modelling framework [18] is entirely deterministic and so does not allow incorporation of uncertainty in the decision criteria. Instead, some built-in functions are provided to facilitate sensitivity analysis, e.g. to examine the change in outcome when each of the criteria are changed in turn by one or more rating categories. So, for example, a criterion with high uncertainty might be examined over a wider range of possible values than one with low uncertainty. This approach did not lend itself to a simple summary of the uncertainty associated with a particular assessment.

The use of Bayesian Networks (BNs) was also investigated as part of PRATIQUE but the scale of the scheme made it too difficult for assessors to assign meaningful values in the large conditional probability tables. Simpler PRA schemes with fewer criteria and/or few rating levels may offer more scope for the development of BNs and the approach was further explored for such a potential scheme within the Prima phacie project. BNs with relatively simple structures and three rating levels are also being developed to model the effect of alternative management measures on risk of pest infestation along a commodity production and export chain [37].

The framework described here incorporates uncertainty in criterion rating but uses deterministic utility functions to integrate the criteria in the same way as DEXi. It provides a limited palette of options both to describe criterion uncertainty and to integrate the criteria in a way that readily communicates all components of risk and uncertainty to risk managers. When tested in PRA workshops, Pest risk analysts thought that the framework accorded with their way of thinking and were able to make reasoned choices between the options and to deconstruct final result to see which elements where most influential in the combined risk rating. They chose the approach from the alternatives considered with considerations of transparency and comprehensibility both being influential in their selection.

The utility functions in the form of matrices were partially completed during the development of models for PRA. The set of uncertainty distributions was also developed at this time. Here, the model is completed by extending the utility functions to include asymmetrical matrices in a single consistent framework. Apart from offering a single consistent set of rules for all the utility functions, these matrices have an arguably better configuration than those specified element by element (Figs. 5 a and b). There are fewer cases where it is possible to traverse the matrix without passing through each rating category in turn, a property described by Cox [38], in the context of risk matrices, as 'betweenness'. The exception is the Round-out matrix where it is possible to move diagonally from 'low' to 'high' without crossing 'medium' (see Fig. 1 and Fig. 5 c). The jump from 'low' direct to 'high' can only happen when *both* input criteria increase in rating at the same time. The Round-out matrix is included however, because it provides a useful concept to integrate certain criteria, where a more extreme value, either very high or very low, is considered particularly influential.

The restriction of both the utility functions and the uncertainty distributions to small numbers of alternatives has the important consequence of reducing extraneous noise in the model. Experience in PRATIQUE and Prima phacie workshops indicated that pest risk analysts were in general uncomfortable about being asked to define frequency distributions or utility functions because it was too open-ended a task. In contrast they were generally able to select the most appropriate of a small set of available options, e.g. whether a utility function should represent the minimum, maximum or be intermediate and whether an uncertainty distribution should be wide or narrow. The limited palette provides the basis for consistency in model specification and for a well-bounded sensitivity analysis, so in cases of doubt it is easy to examine the consequences if other utility functions or uncertainty distributions had been selected instead.

The models can only capture the logic for a generalised situation and differences are expected between the model result and what is judged an appropriate result independently of the model. The purpose of the model is to provide a consistent, repeatable methodology which should be regarded as a baseline to check the consistency of the results derived directly from the assessors without the aid of the model and to help compare different outcomes of different PRAs. As part of the EPPO DSS for PRA, the assessors have access to the models but they are first asked to provide their own summary ratings for each of the main sections of the PRA, Entry, Establishment, Spread and Impact. The task of summarizing each section and its uncertainty is difficult so in addition the model described here, graphical visualisation software was also developed to allow the case summary to be viewed on single page, so facilitating an assessment based on the pattern of all the component ratings and uncertainties when viewed simultaneously (29). Software with a similar objective has also been developed for environmental risk assessments (39) and the use of descriptive tools in parallel to models such as that described here helps ensure that assessor judgement is paramount in the process. Where these assessments differ from the model, the value of the model is to help highlight how the logic pertaining to the particular pest differs from the generalised case (presented by the model) and so act as a check on whether these differences are justified. For example, one of the criteria might properly have much more weight in a specific case than is usual. It is intended to allow a further body of PRA evaluation results to accumulate before reviewing and if necessary modifying the logic of the generalised case represented by the model.

The potential application of models of this kind is not restricted to PRA. Risk assessment schemes exist in fisheries in which large numbers of criteria or indicators with their associated uncertainties are combined to provide an overall measure of ecological, commercial and social risk. The authors are also exploring the application of similar models to schemes used for fisheries certification, and in other projects (40, 41).

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Table I. Descriptions of the five utility functions

Matrix name	Outcome	Applicability
Minimum	The lower of the two ratings; both are necessary conditions	The lower rating constrains the outcome
Round-down	The intermediate between the two ratings but where the intermediate falls between two categories, the lower	The outcome lies between the two ratings but has a tendency to be constrained by the lower
Round-out	The intermediate between two ratings but where the intermediate falls between two ratings and is lower than moderate, the lower; and where higher than moderate, the higher	The outcome lies between the two ratings but is more influenced by a higher or lower rating than a moderate rating
Round-up	The intermediate between the two ratings but where the intermediate falls between two categories, the higher	The outcome lies between the two ratings but has a tendency to be more influenced by the higher
Maximum	The higher of the two ratings; either is a sufficient condition	A lower rating of one component does not constrain the outcome

*Table II. Combinations of pairs of the five symmetric matrix types give nine possible asymmetric matrices, three of which (*x*) were used in the model. The combination maximum/minimum is omitted because it yields a utility function in which one input has zero weight*

	Round down	Round out	Round up	Maximum
Minimum	x	x		
Round down				
Round out				
Round up				x

Fig. 1. The five symmetrical matrices which express varying degrees of constraint of one criterion over the other, together with three of the nine possible asymmetrical matrices derived from these which also express varying degrees of differential influence of the two criteria.

MINIMUM

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	VERY LOW	VERY LOW	VERY LOW	VERY LOW
LOW	VERY LOW	LOW	LOW	LOW	LOW
MODERATE	VERY LOW	LOW	MODERATE	MODERATE	MODERATE
HIGH	VERY LOW	LOW	MODERATE	HIGH	HIGH
VERY HIGH	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH

ROUND DOWN

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	VERY LOW	LOW	LOW	MODERATE
LOW	VERY LOW	LOW	LOW	MODERATE	MODERATE
MODERATE	LOW	LOW	MODERATE	MODERATE	HIGH
HIGH	LOW	MODERATE	MODERATE	HIGH	HIGH
VERY HIGH	MODERATE	MODERATE	HIGH	HIGH	VERY HIGH

ROUND OUT

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	VERY LOW	LOW	LOW	MODERATE
LOW	VERY LOW	LOW	LOW	MODERATE	HIGH
MODERATE	LOW	LOW	MODERATE	HIGH	HIGH
HIGH	LOW	MODERATE	HIGH	HIGH	VERY HIGH
VERY HIGH	MODERATE	HIGH	HIGH	VERY HIGH	VERY HIGH

ROUND UP

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	LOW	LOW	MODERATE	MODERATE
LOW	LOW	LOW	MODERATE	MODERATE	HIGH
MODERATE	LOW	MODERATE	MODERATE	HIGH	HIGH
HIGH	MODERATE	MODERATE	HIGH	HIGH	VERY HIGH
VERY HIGH	MODERATE	HIGH	HIGH	VERY HIGH	VERY HIGH

MAXIMUM

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
LOW	LOW	LOW	MODERATE	HIGH	VERY HIGH
MODERATE	MODERATE	MODERATE	MODERATE	HIGH	VERY HIGH
HIGH	HIGH	HIGH	HIGH	HIGH	VERY HIGH
VERY HIGH	VERY HIGH	VERY HIGH	VERY HIGH	VERY HIGH	VERY HIGH

ROUND DOWN / MINIMUM

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	VERY LOW	LOW	LOW	MODERATE
LOW	VERY LOW	LOW	LOW	MODERATE	MODERATE
MODERATE	VERY LOW	LOW	MODERATE	MODERATE	HIGH
HIGH	VERY LOW	LOW	MODERATE	HIGH	HIGH
VERY HIGH	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH

ROUND OUT / MINIMUM

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	VERY LOW	LOW	LOW	MODERATE
LOW	VERY LOW	LOW	LOW	MODERATE	HIGH
MODERATE	VERY LOW	LOW	MODERATE	HIGH	HIGH
HIGH	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY HIGH	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH

MAXIMUM / ROUND UP

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
LOW	LOW	LOW	MODERATE	HIGH	VERY HIGH
MODERATE	LOW	MODERATE	MODERATE	HIGH	VERY HIGH
HIGH	MODERATE	MODERATE	HIGH	HIGH	VERY HIGH
VERY HIGH	MODERATE	HIGH	HIGH	VERY HIGH	VERY HIGH

Fig. 2. Rating frequency distributions corresponding to a selected rating of 'moderate' (M), at three alternative choices of uncertainty. The proportion of the distribution lying at the modal or selected rating, 90, 50 or 35%, broadly followed IPCC guidelines [25]. The Beta and Truncated Normal distributions were explored, both being appropriately bounded [26]; a Beta distribution is shown here.

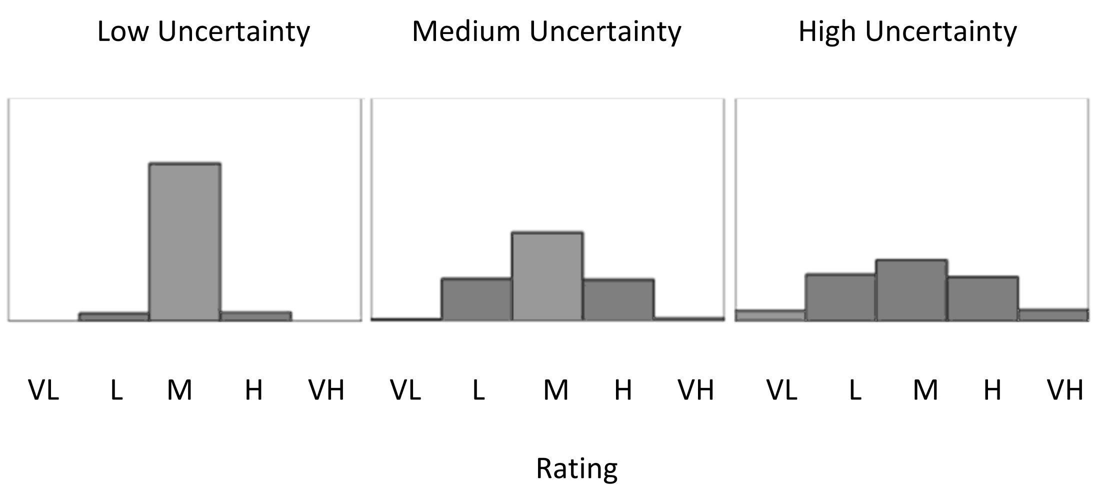

Fig. 3. Illustration of the calculation of combined impact which is determined by: a) the maximum matrix; b) the joint frequency distribution of crop impact and environmental impact; c) the sum of the appropriate cells of the joint distribution. In this example, crop impact is moderate with moderate uncertainty and environmental impact is low with moderate uncertainty.

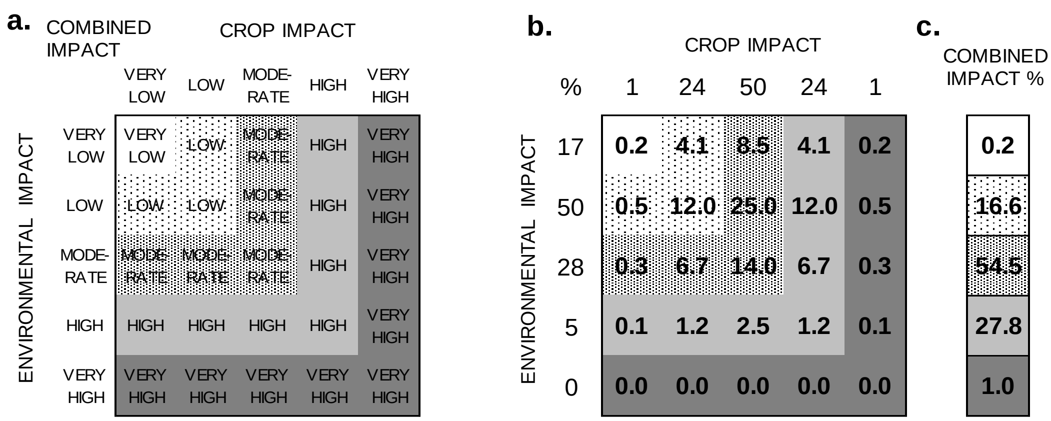

Fig. 4. Examples of the use of four symmetric matrices in the models for PRA

Examples of the use of four symmetric matrices in the PRIMA PHACIE and PRATIQUE PRA

a) ROUND OUT

MOVES ALONG PATHWAY

ASSOCIATION \ VOLUME	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	VERY LOW	LOW	LOW	MODERATE
LOW	VERY LOW	LOW	LOW	MODERATE	HIGH
MODERATE	LOW	LOW	MODERATE	HIGH	HIGH
HIGH	LOW	MODERATE	HIGH	HIGH	VERY HIGH
VERY HIGH	MODERATE	HIGH	HIGH	VERY HIGH	VERY HIGH

Movement along the pathway is a compromise between the ratings for association and volume but is especailly influenced up or down by more extreme

b) MAXIMUM

COMBINED IMPACT

ENVIRONMENTAL IMPACT \ CROP IMPACT	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
LOW	LOW	LOW	MODERATE	HIGH	VERY HIGH
MODERATE	MODERATE	MODERATE	MODERATE	HIGH	VERY HIGH
HIGH	HIGH	HIGH	HIGH	HIGH	VERY HIGH
VERY HIGH	VERY HIGH	VERY HIGH	VERY HIGH	VERY HIGH	VERY HIGH

Either can lead to high impact so the combined impact is determined by the greater

c) MINIMUM

ESTABLISHMENT SUITABILITY

ABIOTIC \ CLIMATE	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	VERY LOW	VERY LOW	VERY LOW	VERY LOW
LOW	VERY LOW	LOW	LOW	LOW	LOW
MODERATE	VERY LOW	LOW	MODERATE	MODERATE	MODERATE
HIGH	VERY LOW	LOW	MODERATE	HIGH	HIGH
VERY HIGH	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH

Either can be a constraint so both the climatic and abiotic conditions must be suitable for the area concerned to be suitable

d) ROUND UP

ESTABLISHMENT NOT INFLUENCED

DESPITE ECOLOGY \ DESPITE MANAGEMENT	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
VERY LOW	VERY LOW	LOW	LOW	MODERATE	MODERATE
LOW	LOW	LOW	MODERATE	MODERATE	HIGH
MODERATE	LOW	MODERATE	MODERATE	HIGH	HIGH
HIGH	MODERATE	MODERATE	HIGH	HIGH	VERY HIGH
VERY HIGH	MODERATE	HIGH	HIGH	VERY HIGH	VERY HIGH

Whether establishment remians uninfluenced by crop management or ecology is a compromise between the two ratings but is more influenced by the higher rating

Fig. 5. Examples of relationships between criteria in the models for PRA which require asymmetric matrices. Cells of the matrices which differ from their original PRA model counterparts are shown with solid outlines.

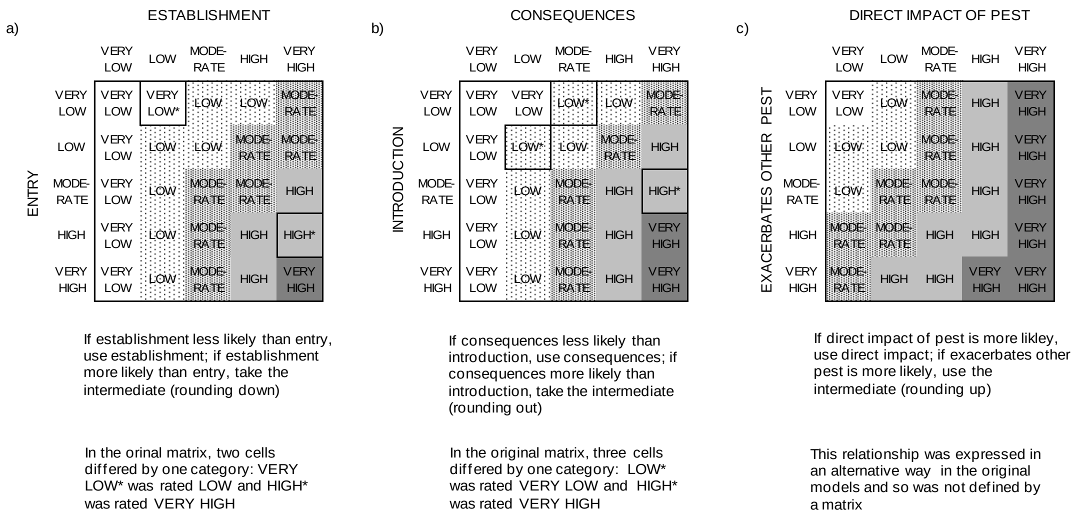

Fig. 6. The top tier of the model hierarchy, modified from that used in the Prima phacie project. Here the basic attributes are not scheme questions but rating distributions derived from sub-models. The utility functions are described in Fig. 1.

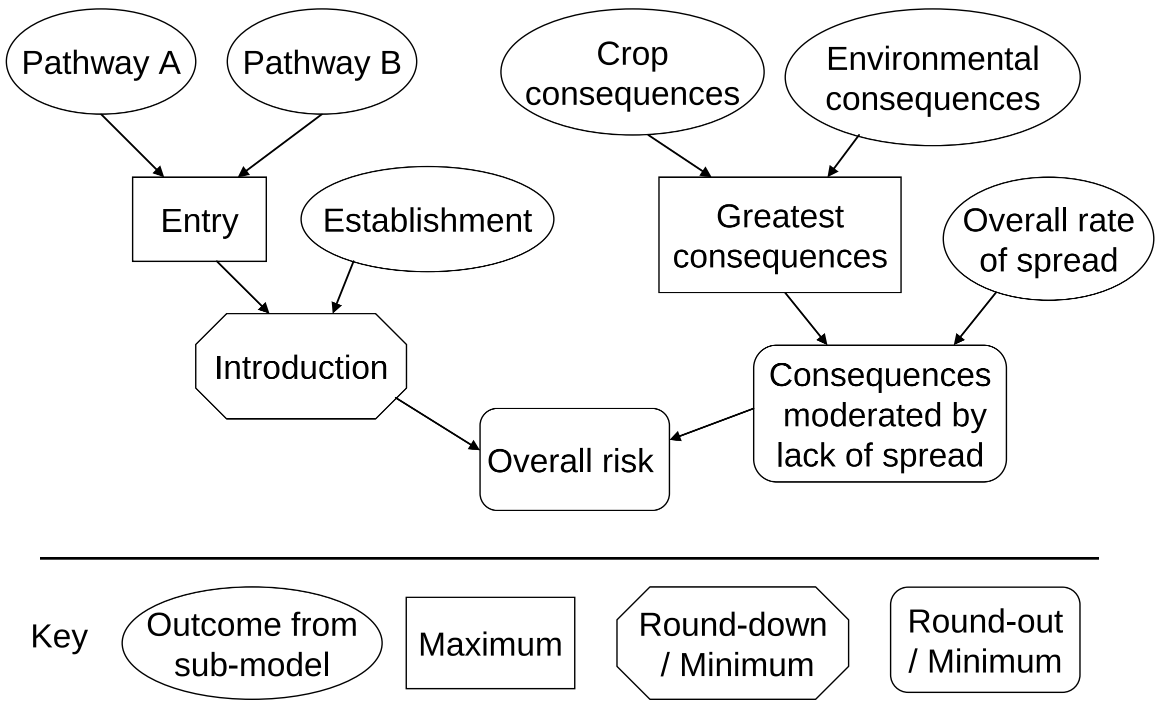

Fig. 7. The sub-model hierarchy for each pathway of entry, modified from that used in the Prima phacie project. The basic attributes are the risk-factors each described by a scheme question. The utility functions are described in Fig. 1.