Untangling Probability Concepts in Qualitative Risk Evaluations

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Abstract

Improved fisheries management requires consistent and transparent risk evaluations, but qualitative judgments are usually necessary to bridge the gap from theory to implementation and from technical details to broader communication. Recent risk assessments in fisheries illustrate the potential benefits and highlight methodological inconsistencies resulting from the particular setting of each case study. These inconsistencies need to be untangled using fundamental probability concepts to identify those aspects that are most relevant to the decision setting. Only then can appropriate qualitative approximations be developed.

Qualitative risk evaluations need to distinguish between evaluating a few distinct outcomes or broad ranges of outcomes. For a distinct outcomes, such as the risk associated with the breach of a hydroelectric dam, quantitative risk assessments consider the severity of each possible outcome and the probability of each outcome. The qualitative approximation for this is the traditional risk matrix, categorizing outcomes on two scales: highly improbable to highly probable and negligible to severe. Uncertainty can be incorporated by specifying ranges along each scale (e.g. event is either highly probable or moderately probable). However, most fisheries decisions deal with a continuous range of possible outcomes, and qualitative approximations need to reflect the shape of the probability distribution, effectively moving towards Bayesian degrees of belief. For example, risk evaluations of conservation units for Fraser River sockeye salmon (*Oncorhynchus nerka*) incorporate the two dimensions of severity (i.e. judging current status) and uncertainty (i.e. judging quality of information) to delineate five distinct risk categories, each with specific implications for stock assessment.

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Risk in fisheries management

The Precautionary Approach to Fisheries (PA2F)

Risk and uncertainty have become fundamental considerations in all aspects of fisheries management. A major milestone in this development were expert consultations organized by the Government of Sweden and the Food and Agriculture Organization (FAO) of the United Nations, which formally defined the precautionary approach to fisheries and discussed how uncertainty should be taken into account in a fisheries context. Specifically, "*The precautionary approach involves the application of prudent foresight. Taking account of the uncertainties in fisheries systems and the need to take action with incomplete knowledge, it requires, inter alia: (a) consideration of the needs of future generations and avoidance of changes that are not potentially reversible; (b) prior identification of undesirable outcomes and of measures that will avoid them or correct them promptly"* (FAO 1995, §6)

Since then, the PA2F has served as a launching point for policy initiatives (e.g. Canada's *Wild Salmon Policy,* FOC 2005) and as a performance standard for fisheries evaluations (e.g. third-party ecocertification programs). Over the same time period, management agencies such as Fisheries and Oceans Canada (FOC) have struggled with the practical implementation of these principles in each step of the annual planning cycle for fisheries (e.g. FOC 2006, de Young 1999).

Components of risk

In common usage, the term risk usually refers to the probability of an undesirable outcome, such as an accident or financial loss; risk and probability are used interchangeably. This interpretation is consistent with the PA2F (FAO 1995, §14) and is the basis for the majority of published risk assessments (e.g. "risk of extinction"). However, this only captures one component of risk – whether the undesirable outcome is likely to occur or not - and misses the crucial element of severity – whether the consequences of the undesirable outcome are small or large. Combining probability and severity yields the technical definition of risk as *expected loss* (e.g. Peterman 2004, Hilborn et al. 2001, Stephen 2001, Peterman and Anderson 1999, Francis and Shotton 1997, Hrudey 1997, Hilborn and Peterman 1995, Huppert 1995, Stephenson and Lane 1995).

When evaluating risks in real-world fisheries settings, both the probability of different outcomes and the magnitude of associated consequences are unknown. They have to be estimated based on available information and reasonable assumptions, introducing substantial uncertainty.

Practical definitions for risk and its components are:

Risk = expected loss = probability of an outcome * severity of its consequences

Probability = chance that an outcome occurs

Severity = magnitude of losses associated with an outcome

Uncertainty = when a quantity is not known exactly (e.g. unknown severity of consequences)

Figure 1 illustrates these components of risk for a simple case with two discrete outcomes, and for the more typical case with a range of possible outcomes.

Table 1 categorizes recently published risk assessments based on the type of analysis used (i.e. quantitative vs. qualitative) and the components of risk explicitly considered (i.e. probability only vs. probability and severity). Each of these assessments was adapted to the circumstances and established practices for the particular decision problem at hand, ranging from non-indigenous species in ballast water to heavy metals in the food chain. The majority of risk assessments were quantitative estimates of probability.

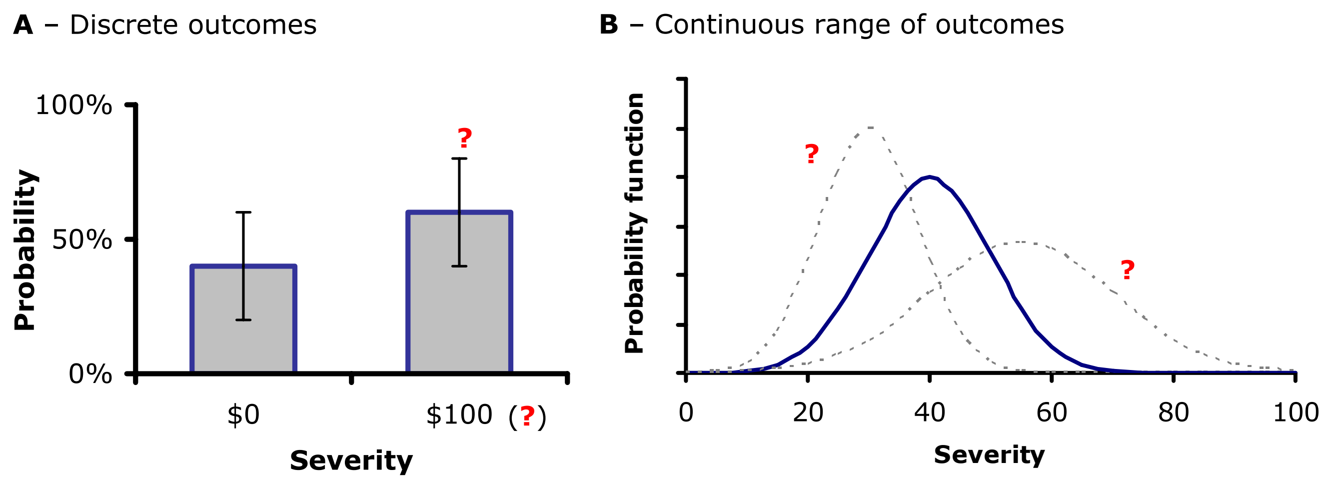

Figure 1. Components of risk.
Panel A illustrates the components of risk for a simple case with two possible outcomes. Expected loss is calculated as the sum of losses associated with each possible outcome, weighted by the probability of each outcome (i.e. risk = 40% * $0 + 60% * $100 = $60). Given imperfect information, there is uncertainty in the height of each bar and in the loss value associated with each outcome. Panel B illustrates the same components of risk for the more typical case with a range of possible outcomes. Expected loss is still calculated as the sum of losses associated with each possible outcome, weighted by the probability of each outcome (i.e. risk = $\int f(z,\mu=40,\sigma=10)\, dz$). Given imperfect information, there is uncertainty in the shape of the probability function.

Table 1: Summary of recent risk assessments published in two fisheries journals.
Papers are categorized based on the assessment approach and the components of risk they incorporate. Included are risk assessments published since the release of guidelines for the precautionary approach to fisheries (FAO 1995) in the ICES Journal of Marine Science and the Canadian Journal of Fisheries and Aquatic Sciences. Note that papers were only included if the definition of risk could be clearly identified.

		COMPONENTS OF RISK	
		Probability only	**Probability and Severity**
ASSESSMENT APPROACH	**Quantitative Estimate**	**28 papers (68%) -** Barry et al. (2008), Dunstan and Bax (2008), Gertzen et al. (2008), Bjørn et al. (2007), Rice and Legacè (2007), Roel and De Oliveira (2007), Skagen (2007), Brickman (2006), Hvingel and Kingsley (2006), Kell et al. (2006), Chaput et al. (2005), Kaplan (2005), Alvarez-Flores and Heide-Jørgensen (2004), De Oliveira and Butterworth (2004), Fogarty and Gendron (2004), Poloczanska et al. (2004), Roel et al. (2004), MacIsaac et al. (2003), MacIsaac et al. (2002), Rueda and Defeo (2001), Powles et al. (2000), Butterworth and Punt (1999), DiNardo and Wetherall (1999), Cass and Riddell (1999), Jonsson et al. (1999), Kann and Smith (1999), Mcallister and Kirkwood (1999), Nickelson and Lawson (1998)	**8 papers (20%) -** Pilling et al. (2008), Gröger et al. (2007), Rueda and Defeo (2003), Hayes (1998), Lane and Stephenson (1998), Gibson and Myers (2004), Borsuk et al (2002), Kuikka et al. (1999)
	Qualitative Approximation		**5 papers (12%) -** Campbell (2008), Therriault and Herborg (2008), Campbell and Gallagher (2007), Braccini et al. (2006), Fletcher (2005)

It is useful to consider the *implicit* assumptions associated with each category in Table 1:

- *If a risk assessment considers only the probability of undesirable outcomes (as in "risk of extinction"), then the implicit assumption is that consequences are of equal magnitude across all cases.* This works well when comparing similar cases, such as the probability of not meeting management targets under alternative harvest strategies for the same stock. However, the implicit assumption of equal consequences presents serious pitfalls when comparing diverse cases, such as species at risk. For example, the local depletion of a keystone species (e.g. pink salmon *Oncorhynchus gorbuscha* in a coastal watershed that relies on marine nutrients) has more severe consequences than the extirpation of a highly unique species that isn't such a crucial component of the regional ecology (e.g. benthic Vananda Creek stickleback *Gasterosteus sp.*). However, a highly-adapted local species is a good indicator of broader ecosystem conditions and provides early warning signs of more severe consequences. Either way, the process of prioritizing research and recovery measures across all species at risk should include some consideration of severity, even if it is only a rough qualitative judgment.
- *If a risk assessment considers both the probability of and severity of undesirable outcomes, then the implicit assumption is that the quality of information is roughly the same for both components of risk.* In most cases that doesn't hold true. Difficult questions of scope (i.e. which consequences are included) and distribution (i.e. who suffers the consequences) move to the forefront of the analysis and result in estimates of severity that differ by many orders of magnitude. In comparison, methods for estimating the probability component of risk have been more solidly established, and provide a more defensible basis for public policy discussions.
- *If a risk assessment is set up to rely on quantitative estimates, then implicit assumptions are that sufficient information can be compiled, that the scope of feasible analysis roughly matches the scope of the decision problem at hand, and that sufficient resources are available to complete the analysis*. This typically holds true for large-scale or high-priority issues, such as salmon conservation strategies on the Columbia River (e.g. Stanley and Doyle 2003, NRC 1996). However, the vast majority of decisions in fisheries management occur in a day-to-day operational setting where quantitative risk assessments are just not feasible. Decision support for these common situations means developing a toolbox of rough, qualitative approximations that encourage risk-based decisions consistent with the principles of the PA2F. While the majority of published risk assessments were quantitative estimates of probability (top left quadrant of Table 1), the risk assessment methods most useful to front-line fisheries managers are qualitative approximations of probability and severity (bottom right quadrant of Table 1).

Probability concepts

Two distinct schools of thought, *frequentist* and *Bayesian*, are engaged in an on-going theoretical debate about the concept of probability and its interpretation in particular problem categories, such as parameter estimates, confidence intervals, and forecasts (e.g. Bayarri and Berger 2004, Gelman 1998, Huppert 1995, Efron 1986). Box and Tiao (1973) discuss the theoretical foundation for Bayesian methods in great detail. Punt and Hilborn (1997) provide a step-by-step description and review fisheries applications.

Glossing over all the nuances debated by statisticians, a practical distinction between these two views of probability is how they interpret confidence intervals:

- The frequentist approach is to evaluate observed samples and infer the characteristics of the source population. Probability is interpreted as a relative frequency of occurrence, such that an 80% confidence interval translates into *80% percent of confidence intervals estimated from different samples of the same population contain the true value.*

- The Bayesian approach is to start by explicitly stating up-front assumptions about the population (i.e. prior probability distribution), to confront those assumptions with sample information (i.e. likelihood) and to arrive at modified assumptions (i.e. posterior probability distribution). Probability is interpreted as a degree of belief, such that an 80% confidence interval translates into a *high level of confidence that the true value falls within the interval.*

Through a Bayesian lens, the distributions in Figure 1b capture the best estimate (e.g. of abundance) in the location of the peak, and reflect the quality of information in the spread (i.e. narrower distribution = more confident in estimate). The Bayesian approach naturally combines information of different quality from different sources, and lends itself to incorporating expert judgment. For example, Pestal (2004) describes an in-season prediction model that starts with a prior assumption (e.g. conditions this year probably similar to the period 1980-1990), and updates weekly abundance estimates based on in-season catch data, weighted by the uncertainty in each week's sample. Predictions for weeks with highly uncertain data (e.g. unfavorable river conditions) benefit from better-quality data in previous weeks.

Fisheries managers typically have to take a considerable leap from quantitative analyses to the decision problem at hand, and the differences between frequentist and Bayesian views of probability tend to blur in practice. For example, consider extrapolating from simulation to reality. If a simulated management strategy depletes a simulated fish stock to critically low abundance in 5-15% of scenarios (i.e. frequency), then the analyst may report a 5-15% probability that the actual management strategy would deplete the actual stock. This leap implicitly moves one into the realm of Bayesian degrees of belief. The Bayesian approach just makes this step explicit and tractable.

Qualitative risk approximations

Risk matrix

Figure 1A illustrates the components of risk for the simple case with two outcomes – the undesirable event either occurs, or it doesn't. The risk matrix in Figure 2A captures the same scenario in a format that supports discussion with a broader audience and allows direct comparisons between alternative options. Option 1 corresponds directly to the risk portrayed in Figure 1A. Option 2 results in a smaller probability of undesirable outcomes, but with more severe consequences, and larger uncertainty in the estimate of severity.

Qualitative approximations simply overlay a coarser grid onto the risk matrix, as illustrated in Figure 2B. All of the components of risk are retained, and lend themselves to a succinct summary of outcomes (i.e. "probably severe"). This is the approach taken by Fletcher (2005) to prioritize issues for seven Western Australian fisheries. For each issue, performance was evaluated in 4 steps:

- Assign one of six levels of consequence, ranging from negligible (0) to catastrophic (5) to assess fishery impacts, with context-specific definitions of each level (e.g. habitat: Minor = 1 = measurable but localized impact affects 1 to 5% of total habitat area)
- Assign one of six levels of probability, ranging from remote (1) to likely (6), with specific definitions of each level (e.g. possible = 4 = some evidence to suggest this is possible here). Note that each of these evaluations can be interpreted as a Bayesian degree of belief.
- Define an overall risk score = consequence score * probability score
- Specify a range of reporting requirements and management actions triggered by the risk scores (e.g. full risk assessment report required if risk score > 7, significant additional management activity needed if risk score > 20).

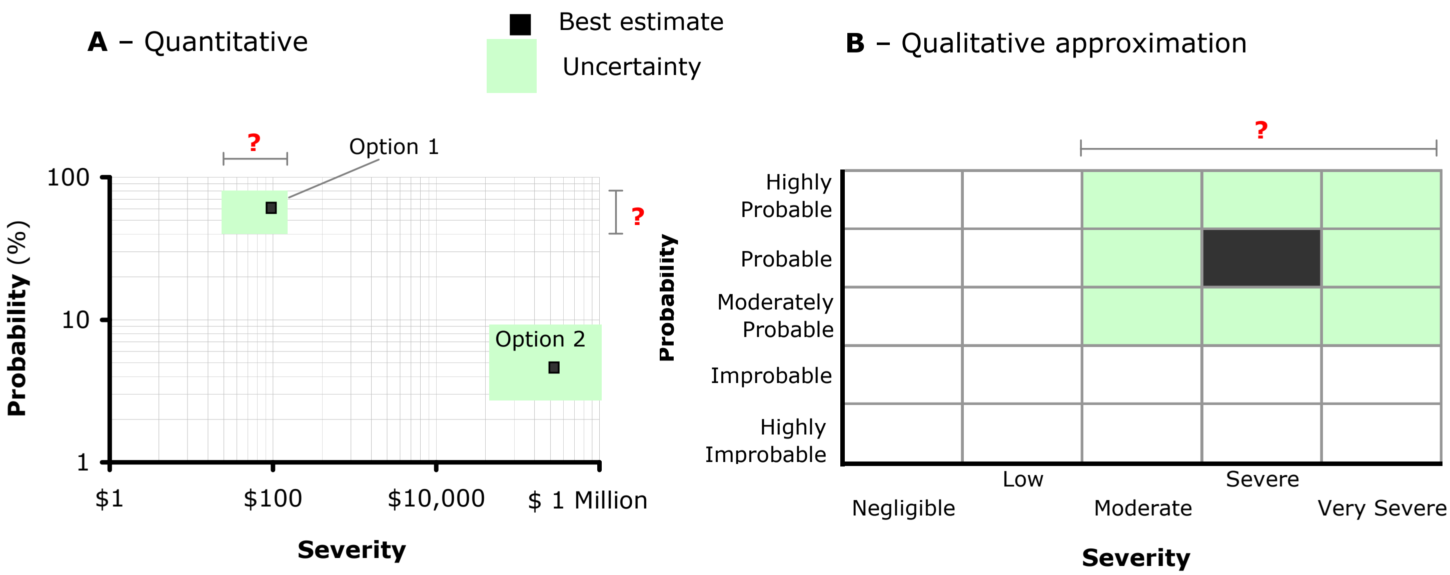

Figure 2. Risk matrix.
A risk matrix maps out the two components of risk on a grid, allowing a direct transition from quantitative risk assessment to qualitative approximation. Note that the probability axis could be relabeled in terms of frequent/infrequent to reflect the number of expected occurrences (e.g. ballast water spills).

Probability distribution

Figure 1B illustrates the components of risk for a continuous range of outcomes - each magnitude of consequence has an associated probability. Risk assessment is based on the shape of the distribution, and qualitative approximations need to capture both the peak and the spread. The peak corresponds to severity, as in the risk matrix above, but in the Bayesian view the spread corresponds to *uncertainty*, not *probability*. The narrower the distribution, the more confidence it expresses in the assessment of severity (i.e. stronger degree of belief). This is a subtle difference with considerable implications. For example, the question put before the analysts shifts from "*What are the losses associated with depletion of this stock, and how likely will these losses occur?"* to "*What is the current status of this stock, and how much confidence do you have in your evaluation of its status?"*. Figure 3 illustrates the approach and classifies probability distributions into 5 risk categories. This is the approach taken by Pestal and Cass (2009) to prioritize resource assessment activities for Fraser River sockeye salmon (*Oncorhynchus nerka*). The three risk factors of status, vulnerability, and human impact were evaluated for each of the conservation units (i.e. functionally distinct population groups) identified under the *Wild Salmon Policy* (Holtby and Ciruna 2007, FOC 2005). Indicators for each risk factor were evaluated as follows:

- Assign one of six levels of severity, ranging from negligible (1) to very severe (5), with context-specific definitions of each level (e.g. recent abundance relative to long-term average: *"Low"* = 3 = 26-50%)
- Assign one of six levels of uncertainty, ranging from low (1) to high (4) and unknown (10), with context-specific definitions of each level (e.g. recent abundance relative to long-term average: Moderate uncertainty = 3 = 3 or 4 escapement observations based on visual estimates in last 4 years, and another 30 observations or more since the 1940s.)
- Classify conservation units into risk categories, based on the combination of severity and uncertainty (Figure 4). Preliminary risk evaluations proved useful for identifying information gaps, sorting sockeye stocks into risk categories, establishing risk profiles for each management grouping of Fraser sockeye, and comparing those risk profiles to past patterns of assessment coverage.

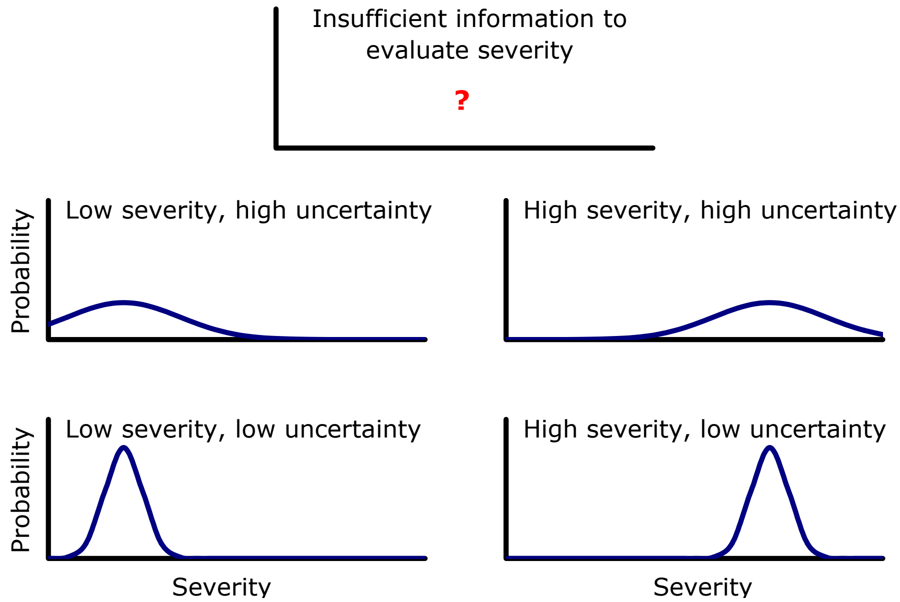

Figure 3. Qualitative approximation for probability distributions.
In the Bayesian interpretation the peak corresponds to severity and the spread corresponds to uncertainty. The narrower the distribution, the more confidence it expresses in the assessment of severity (i.e. stronger degree of belief).

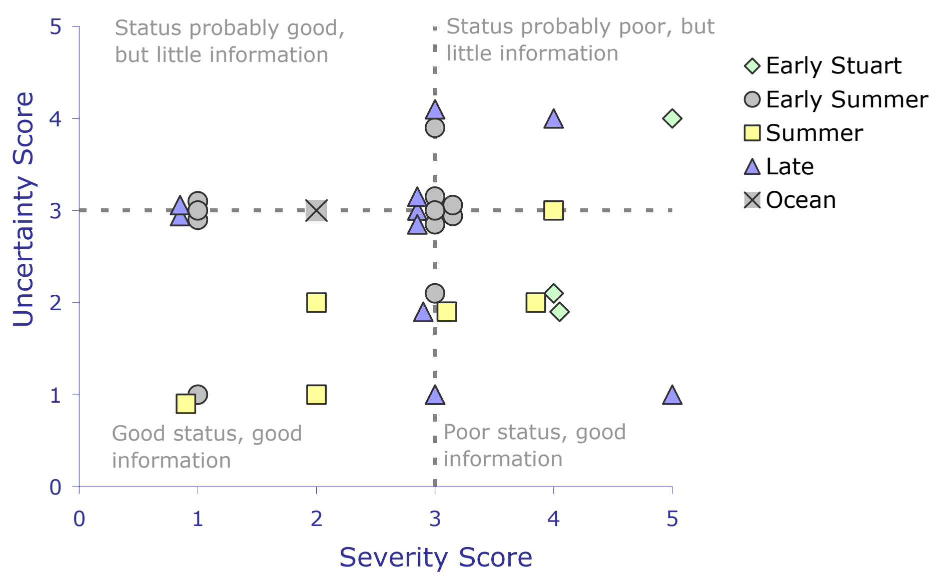

Figure 4. Qualitative risk evaluations for 32 preliminary conservation units of Fraser River sockeye.
Information was insufficient for evaluating the status of an additional 7 preliminary conservation units. Status evaluations combine six individual indicators: trend in abundance, largest decline by cycle line, recent abundance, recent abundance vs. long-term average, recent abundance vs. highest observed, and recent abundance vs. current capacity. Updated evaluations for the finalized conservation units are included in Pestal and Cass (2009).

Discussion

Qualitative approximations of risk assessments are a highly effective format for compiling expert judgment. They establish a consistent frame of reference for the raw data and encourage analysts to explicitly state their opinions based on available information and their experience with similar cases.

Both components of risk should be considered in the initial stages of a qualitative evaluation to ensure that the shortcut retains the most relevant elements of the decision problem. For example, the assumption of roughly similar magnitude of consequences can be justified when comparing the *relative* risk of stock depletion under alternative harvest strategies. The same assumption is harder to justify, however, when dealing with highly diverse comparisons, such as the extinction risk for species with very different roles in the regional ecosystem (e.g. pink salmon vs. stickleback).

In all aspects of fisheries management, it remains a fundamental challenge to capture and communicate the essence of risk-based decisions in a format the lends itself to transparent communication with a broad range of stakeholders. Qualitative approximations are a useful addition to the decision-support toolbox for fisheries management as long as they reflect the components of risk that are relevant in each particular setting, are reasonably consistent across cases, and are thoroughly documented.

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