FISH and FISHERIES

FISH and FISHERIES, 2010, **11**, 341–365

Risk management for fisheries

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Abstract

Risk management methods provide means to address increasing complexity for successful fisheries management by systematically identifying and coping with risk. The objective of this study is to summarize risk management practices in use in fisheries and to present strategies that are not currently used but may be applicable. Available tools originate from a variety of disciplines and are as diverse as the risks they address, including algorithms to aid in making decisions with multiple stakeholders, reserves to buffer against economic or biological surprises, and insurance instruments to help fishermen cope with economic variability. Techniques are organized in a two-stage framework. In the first stage, risks are identified and analysed. Strategies presented in this category focus on decision analysis, including multicriteria decision-making tools, and the related concept of risk assessment. Then in the treatment stage, identified risks can be transferred, avoided, or retained using tools such as the Precautionary Approach, portfolio management, financial contracts to manage price risk and horizontal integration. Published fishery applications are reviewed, and some empirical examples of risks and risk management using US fisheries data are presented.

Keywords Biological risk, decision analysis, economic risk, fisheries management, risk management, socioecological systems

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Received 24 Jun 2009
Accepted 6 Apr 2010

 DOI: 10.1111/j.1467-2979.2010.00363.x

Introduction

Risk pervades modern day fisheries management where uncertainty, variability, scarcity and multiple objectives are common terms. Two major drivers underlie this: the inability to predict the behaviour of complex socioecological fishery systems (Sissenwine 1984; Hilborn 1987; Charles 1998) and a transition of ocean ecosystems away from frontier settings of untouched and unlimited resources to scarce resources and conflicting goals (Hanna 1997). In short, fisheries management is the business of making trade-offs in a complex, unpredictable and variable world. Risk management methods provide pragmatic means of navigating this increasing complexity by systematically identifying and coping with risk.

Fisheries science has reacted to the mounting challenges to successful management, for example by making recommendations to incorporate risk and uncertainty into the decision-making process (Walters 1986; Ludwig *et al.* 1993; Rosenberg and Restrepo 1994), however risk management as a pragmatic and proactive framework remains underutilized. Available tools originate from a variety of disciplines and are as diverse as the risks they address, including algorithms for making decisions involving multiple stakeholders, reserves to buffer against economic or biological surprises, and insurance instruments to help fishermen weather market variability.

Previous authors have synthesized information on uncertainty (Charles 1998; Harwood and Stokes 2003), risk (Francis and Shotton 1997) and risk assessment (Lane and Stephenson 1998; Harwood 2000) in fisheries, and some have called for risk management as a logical progression (Hilborn *et al.* 2001). The motivation is straightforward. Political mandates to incorporate uncertainty and multiple objectives into fisheries management can be accommodated through the risk management framework (e.g. NOAA 1997; Weeks and Berkeley 2000; USDC 2007). While many risk management strategies are designed for regulators or management agencies, fishery participants stand to benefit as well by utilizing strategies to cope with the many sources of variability in socioecological systems in maintaining livelihoods. Indeed, many risk management strategies were developed in response to the difficulties of making a living by farming on land (the US Department of Agriculture has a division devoted to risk management called the Risk Management Agency).

Some innovative work applying risk management to fisheries has been carried out (see below). For example, decision analysis techniques were used in designing multiple objective management plans for pelagic longlining in Hawaii (Leung *et al.* 1998). Sanchirico *et al.* (2008) applied portfolio analysis to optimize multiple stock management in the Chesapeake Bay. Other strategies to cope with unpredictable variability that have not been formally identified as risk management are used by fishery participants, like the formation of fishermen cooperatives to share production risk in herring fisheries (Leal 2008). An effort to develop the concept in the broader fisheries management community or to synthesize risk management currently in use, however, is lacking. Techniques from a wide range of disciplines including agriculture, finance and managerial science offer tools which can aid fishery socioecological systems in coping with an unpredictable and variable world.

The objective of this study is to summarize risk management practices in use in fisheries and to present strategies that are currently not taken advantages of but may be appropriate for fisheries management. The section ‘Risk, risk management and the fisheries context’ briefly outlines the concepts of risk and risk management, highlighting some sources of risk in fisheries. The section ‘Survey of risk management strategies in use or applicable to fisheries’ presents a survey of risk management tools in use or useful for fisheries management. Cited references offer fishery-specific examples where applicable. To help clarify terminology originating from different risk management disciplines, the appendix presents a partial glossary of terms.

Defined terms are bolded in the text. Finally, the section ‘Summary and conclusions’ provides closing remarks. This review is intended for a broad range of readers involved in fisheries management, and aims to provide a survey of topics with entry points into the relevant literatures; technical details of risk management tools are not a focus.

Risk, risk management and the fisheries context

‘Our world is so constructed that the physical and material benefits we most desire are sprinkled with the seeds of disaster (Slovic *et al.* 2000).’ A first step in exploring risk management is to examine risk in fisheries and its causes. Risk is an intuitive concept to humans; everyone deals with it on a daily basis in making decisions. Any risk involves three underlying components (based on concepts from: Athearn 1971; Crockford 1991; Rowe 1994; Kangas and Kangas 2004): a variable state of the world, imperfect knowledge on the state of the world, including in the future, and a desired state of the world. The term ‘desired’ invokes subjectivity; the effects of risks are dependent upon who bears them. In short, a **risk** entails the ideas of variability, uncertainty and loss, leading to the following definition: a chance of adverse effects from deviations from expectations. Note that a risk is a possibility of a bad thing happening, whereas a **realized risk** is an actuality, i.e. an adverse outcome has transpired.

While each discipline dealing with risk management has its own notion of risk, the definition suggested above is quite general. It is similar to the concept of risk in economics and investment theory, which focus on the variance of deviations from expectations (e.g. the mean-variance maxim, Markowitz 1952; Brachinger and Weber 1997). Furthermore, it is consistent with the concept of risk as adopted by the Food and Agricultural Organization (FAO) whose vision of a natural resource management plan under the **Precautionary Approach** includes decision rules to deal with deviations from expectations (FAO 1996; Punt 2006).

Using the definition suggested above, there are myriad risks in fisheries management and their identification is of critical significance. Uncertainty is widely regarded to be pervasive in fisheries (FAO 1995; Charles 1998; Weeks and Berkeley 2000; Harwood and Stokes 2003), and risks can be identified simply by following the sources of variability and uncertainty as these drive deviations from expectations. Table 1 outlines some common risks affecting the functions of different parts of a fishery system. Multiple risks can be associated with a function. For example, in regulating catch, management agencies face the risk of failing to satisfy social goals like employment or seafood production if they are too conservative, and they face the risk of failing to protect the resource if they fish too aggressively. This was the case with the unfortunate collapse of Newfoundland cod beginning in the late 1980s. Managers, expecting stock size based on model output and pressured by industry, recommended total allowable catches that were too high when the true state of the world was poor recruitment and a declining stock. The ultimate results of unpredictable and uncertain population dynamics were management decisions leading to the collapse of the fishery at great social and economic cost (Hutchings and Myers 1994; Walters and Maguire 1996; Schrank 2005).

Equally important as identification is the task of dealing with risk. **Risk management** is a loose term for the general process of identifying, characterizing and reacting to risk. Dorfman (2008) offered a straightforward definition, ‘the logical development and implementation of a plan to deal with potential losses.’ Crockford (1991) offered a more comprehensive definition, focused on corporate management, but equally applicable to a natural resource system: ‘the identification, measurement, control and financing of risks which threaten the existence, the assets, the earnings or the personnel of an organization, or the services it provides.’ The focus in either case is the pragmatic goal of minimizing the effects of unpredictable variability.

Risk management comprises two stages (Fig. 1). In the first, risks are identified and characterized. Then in the treatment stage, they are dealt with (Crockford 1991; Outreville 1998). With the recognition of uncertainty and advances in computational statistics, such as Bayesian analysis, fisheries science has seen large advances in the first phase, which is often referred to as risk assessment (Francis and Shotton 1997; Lane and Stephenson 1998).

The treatment phase can be broken down into three avenues for handling risk: avoid, transfer or retain risk. In avoidance, management decisions are made to forego risky prospects, for example by deciding not to develop a new resource. In transfer, risks can be shifted in whole or in part to another

Table 1 A partial list of risks affecting the functions of components of a fishery system. Risks do not necessarily correspond with any one function and can simultaneously affect multiple functions.

	Function	Example risks
Biological resource	Biomass production Habitat provision Biodiversity, genetic diversity storage Nutrient/chemical cycling Climate regulation Recreational/cultural opportunity provision	Stock depletion Habitat degradation Pollution Exotic species introductions Climate change Natural disasters Disease Genetic stock structure changes Species interactions/ecosystem effects, e.g. trophic cascades
Management agencies	Regulate and allocate harvest Protect habitat Collect data and perform research Stock enhancement Enforcement and compliance	Failure to achieve social benefits goals through overly cautious harvest Failure to achieve conservation goals through overly aggressive harvest Funding changes
Fishermen, fishing communities, fishing industry	Harvest Process Market	Catch fluctuation Price fluctuation Cost fluctuation Changes in rights to resource use Personal injury Equipment failure Employment loss

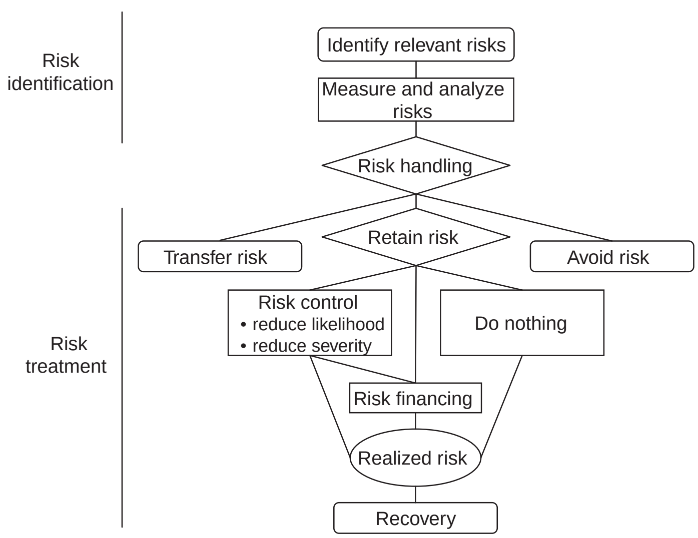

Figure 1 A risk management framework. Rounded boxes are entry and exit points into the risk management process. Rectangles, diamonds and ovals denote actions, decisions and chance events, respectively.

entity that is better able to bear them, for example through insurance or by sharing risk over a pool of individuals.

If the decision is made to retain risk, several options are available. Risk control attempts to reduce the likelihood and/or the magnitude of an adverse outcome. Note that some risks are uncontrollable, such as natural disasters. Another option is to finance risk by making preparations to absorb realized losses. Alternatively, a decision can be made to 'do nothing' and absorb realized risks with no preparation. This encompasses cases where extant risks go unidentified, or when no action is taken on identified risks citing a lack of sufficient information to understand the problem. A final measure to handle retained risks is risk recovery, where efforts are taken to improve the response time of a system after a realized adverse outcome.

The multitude of risks in ocean resource systems presents considerable challenges for successful management (Table 1). Yet, decisions must be made and dealing with risk will be an important charge. The following section provides a survey of risk management strategies that are in use or applicable to fisheries management which variously apply to regulators, policy makers, or fishery-dependent entities including fishing communities, processors and fishermen.

Survey of risk management strategies in use or applicable to fisheries

Fishery management problems are diverse, necessitating an array of solution strategies. Following the risk management framework suggested above (Fig. 1), methods are grouped based upon core approaches: decision analysis and risk assessment, risk avoidance, risk transfer, risk control and risk financing. The control category is further broken down into diversification and the portfolio effect, and price risk management. Table 2 synthesizes information about the discussed risk management strategies, noting the target user of the strategy based on a generic fisheries management process in Fig. 2, and some characteristics of the types of problems to which they apply.

These suggested classifications are for organizational purposes and are not strict. For example, insurance policies to transfer risk also involve risk financing by storing away revenues in the form of insurance premiums for eventual losses. While this survey is not exhaustive, it covers the predominant forms of risk management that are in use or may be applicable to fisheries. One notable exception is technology as a risk management strategy. Technology may be adopted to reduce the variability component of risks. Obvious examples in the fisheries context are the use of aquaculture to avoid production variability associated with wild capture fisheries, or the use of hatcheries to stabilize wild harvests. These examples raise an important point: technology results in a new set of risks. Hatchery fish may compete with wild stocks (e.g. Naish *et al.* 2008) and aquaculture equipment may fail. Ultimately, the decision to adopt a technological solution must satisfy case-specific cost–benefit criteria where benefits are net of the new set of risks that arise; technological management options are not discussed further in this survey.

Identify and analyse risk: decision analysis and risk assessment

The dominant form of risk management used in fisheries and natural resource management is **decision analysis** (e.g. Harwood 2000; Herath and Prato 2006; Mendoza and Martins 2006). Decision analysis tools are systematic means of evaluating both quantitative and qualitative data to select a plan of action in the face of multiple and conflicting objectives (Haimes 1998; Linkov *et al.* 2006). They are well suited for fisheries applications because they address the multi-use nature of ocean resources, incorporate the many vested stakeholders throughout the decision process, and are transparent. Decision analysis qualifies as risk management by addressing exposure to risk and attempting to minimize effects of realized risks in light of stakeholder preferences (as noted in section 2, risk is subjective).

A generic decision analysis process is as follows (Lahdelma *et al.* 2000): (i) describe the problem, i.e. objectives, and relevant stakeholders; (ii) define a set of proposed actions and performance criteria; (iii) evaluate the performance of alternative choices; (iv) select a decision tool to digest the performances from part (iii), incorporating stakeholder preferences; and (v) propose a preferred choice or a set of choices. The poorly defined terms of risk analysis and risk assessment are generally part of or incorporate the decision analysis process (Haimes 1998). For example, the US Department of Defense Systems Management College defines risk assessment as the identification and quantification of risks, step (i) above, and risk analysis as the outcomes of different risk inputs, i.e. alternative performance evaluation, steps (ii)–(iii) above (Analytic Sciences Corporation 1989). For the purposes of this article, risk assessment is not specifically addressed as it is nested in the decision analysis process.

Table 2 Risk management strategies applicable in fisheries. Target users correspond to the generic fisheries management process in Fig. 2.

Strategy	Target user	Strategy and problem characteristics	Target outcome
Decision analysis and risk assessment			
MCDM: goal programming, multi-objective optimization	PM, PA, MB, RA, RM	Trade-offs dominate, many stakeholders and objectives; preferences defined in terms of targets and weighted objective functions; policy/regulation selection minimizes risks of failure to achieve management goals	Optimal set of policies/regulations
MCDM: analytic hierarchy process, outranking	PM, PA, MB, RA	Trade-offs dominate, many stakeholders and objectives; quantify degree of preferences amongst trade-offs in policy/regulation selection, minimize risk of stakeholder alienation and objective failure	Ranked set of policies/regulations
MCDM: scenario planning, cognitive map, influence diagram	PM, PA, MB, RA RM	Ignorance of a complex system dominates; evaluate hypothetical scenarios to minimize realization of risks and objective failure, highlight critical areas of systems through mapping	Optimal policy/regulation, contingency plans
Option value	PM, PA, MB, RA	Decisions are irreversible; value to learning and decision delay, choose actions to minimize risks of foregone benefits	Min. risks or max. benefits across time
Adaptive management	PM, PA, MB RA, RM	Initial decision dominated by uncertainty, but decisions are repeated; recognize value of information and learning, iterative process of updating information to reduce uncertainty and risks of objective failure	Management that improves over time
Management strategy evaluation	PM, PA, MB RA, RM	Computer simulation of population dynamics, data and implementation uncertainties; recommendations for management strategies that perform well in the face of uncertainty are passed to decision makers	Uncertainty-robust management
Avoid risk			
Precautionary approach	PM, PA, MB RA, RM	Uncertainty of system dynamics and action outcomes overwhelm predictive abilities; philosophy of risk aversion to avoid bad surprises	Robustness in an uncertain world
Case-by-case risk identification	PM, PA, MB RA, RM, RU	Part of a broader risk assessment process, identify critical risks and choose management actions to avoid them	Reduced set of potential risks
Transfer risk			
Catch & revenue insurance	RU	Specific to income variability; share risks to improve coping ability	Income smoothing
Retain risk			
Diversification/generalization	PM, MB, RU	Benefits derive from a portfolio of assets; control performance variability by increasing the types and numbers of utilized assets	Variability coping, reduce risk exposure
Portfolio selection theory	PA, MB, RA	Exploit statistical averaging and covariation across performance streams to construct benefit-maximizing portfolios at an accepted risk level	Efficient portfolio
Portfolio management: value-at-risk	PA, MB, RA	Characterize exposure to portfolio performance risk through probabilistic distributions of potential losses	Policy/regulation of acceptable risk
Marketing timing	RU	Control exposure to market risk by spreading income flow over time	Income smoothing
Forward contracting & futures	RU	Reduce uncertainty of income over time through contracting	Increase income certainty

Table 2 (Continued).

Strategy	Target user	Strategy and problem characteristics	Target outcome
Vertical integration	RU	Reduce exposure to market risk by internalizing transactions, revenue stream further down value chain	Increase income level & certainty
Horizontal integration	RU	Pool assets to reduce market variability risk, gain bargaining leverage	Increase income level & certainty
Finance risk			
Buffer: marine reserves	PM, PA, MB RA, RM	Uncertainty overwhelms predictive abilities, realized risks are acceptable or unavoidable; accumulate biological reserves to absorb losses	Cope with realized biological risks
Buffer: financial reserve	PM, PA, MB RA, RM, RU	Financial reserves to absorb realized risks	Cope with realized economic risks

MB, management body; MCDM, multicriteria decision making; PA, policy analyst; PM, policy maker; RA, resource analyst; RM, resource manager; RU, resource user.

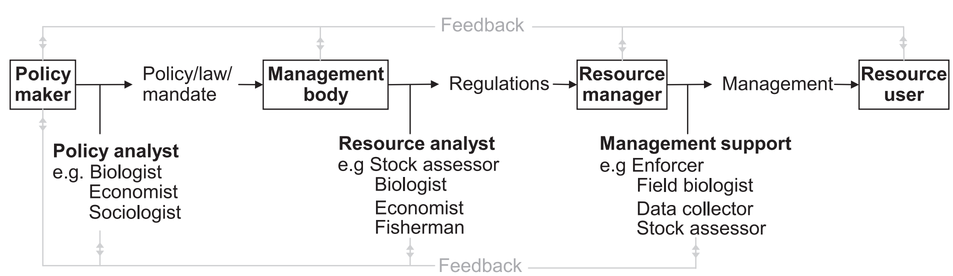

Figure 2 A generic fisheries management process under a central authority. Bold text indicates actors in the process which correspond with 'target users' from Table 2. Boxes indicate levels in the management hierarchy with the corresponding support staff listed below. Arrows indicate the flow of activity. Feedback, denoted in light grey, permeates the systems.

Reviews demonstrating fisheries management-specific applications of decision analysis and the related risk assessment are available (Francis and Shotton 1997; Punt and Hilborn 1997; Lane and Stephenson 1998). For the particular class of decision analysis tools called **multicriteria decision making** (MCDM; see below), see Mardle and Pascoe (1999), Leung (2006), and Kjaersgaard (2007) for fishery-specific applications, and see Linkov *et al.* (2006) and Mendoza and Martins (2006) for applications in a broader natural resource management context. Key decision analysis techniques are outlined below, expanding on some topics that are currently not well-known or have not been previously reviewed in a fisheries science context. MCDM is discussed first, followed by methods that incorporate learning. This section concludes with discussion of **management strategy evaluation** (MSE), a form of decision analysis specific to fisheries management that explicitly recognizes uncertainty, utilizing components of MCDM, as well as methods that incorporate learning.

Multicriteria decision making

Most decision analysis applications in fisheries management involve multiple and conflicting goals, such as stock size, catch, employment and habitat effects (Crutchfield 1973). Single objective applications, for example maximizing the net present value of a stock of fish using dynamic programming (Clark 1990), are rare. Even with a single goal to maximize net present value, a wealth allocation decision will ultimately need to be made which requires making trade-offs amongst stakeholders' interests. In multiple goal problems, component objectives are interrelated so that it is generally impossible to simultaneously maximize each separately. Trade-offs emerge as an increase in one objective comes at the cost of another. MCDM tools provide means of navigating trade-offs by incorporating stakeholders' preferences over outcomes into underlying objective functions (Belton and Stewart 2002). The wide array of MCDM tools can be loosely categorized into 'hard', systematic and quantitative, and 'soft', systematic but predominately qualitative, methods (Mendoza and Martins 2006). The hard methods can be further categorized into **multiple objective optimization** techniques and **decision aids**. The hard category will be discussed first.

Multiple objective optimization

The dominant techniques in the multiple objective optimization category of hard MCDM tools include **goal programming** and **multi-objective utility maximization**. The basic approach here is to create a function of interest to optimize that incorporates multiple goals like harvest and employment. Optimization is conducted under constraints that are designed to mirror the workings of the system, including threshold performance targets and system dynamics, for example positive catch and logistic growth dynamics of the fish stock. Due to the complex nature of multiple objective problems, optimization is carried out numerically.

Goal programming frames the optimization in terms of performance targets where the objective function, called the achievement function, minimizes deviations from decision makers' targets. Stakeholder preferences are incorporated into the process by setting performance targets, i.e. goals, as well as specifying relative importance weights amongst goals. This form of MCDM incorporates the notion of risk insomuch that failures to achieve desired goals are minimized. For example, Mardle *et al.* (2000) and Pascoe and Mardle (2001) used nonlinear goal programming to examine catch allocation and fleet configuration policies in the North Sea noting that a goal of profit maximization results in employment loss risks.

Multi-objective utility maximization MCDM is similar to goal programming in construct, however the optimized function of interest is a weighted additive or multiplicative benefits function. Weights signify stakeholder preferences and performance criteria evaluate satisfaction of the underlying objectives. Here, contributions to the benefit function are maximized, whereas in goal programming deviations from targets are minimized. While goal programming has conventionally been used in cases with nearly continuous decision options, like harvest rate or per cent allocation amongst fleets, a form of multi-objective utility maximization called **multi-attribute decision tools** can be used in cases where the decision options are a small set of discrete choices. For example, Hilborn and Walters (1977) used multi-attribute decision tools to evaluate a set of wild stock enhancement policies with a diverse group of stakeholders representing the fishing industry, management agencies and conservationists.

A major critique of the goal programming and multi-objective utility maximization approaches is that they require the formulation of stakeholder's preferences included in the models as objective function weights. The simple weights may not accurately reflect true preferences which may change when options are added or removed from the choice set (Lee and Olson 1999; Lahdelma *et al.* 2000). One method to address this is to conduct sensitivity analysis, presenting model outcomes over an array of preference weightings. This approach been referred to as **generating methods** (Mardle and Pascoe 1999; Kjaersgaard 2007). Kjaersgaard *et al.* (2007) offered another solution by using the MCDM method called **analytic hierarchy process** (AHP; see below), a formal preference elicitation technique, to more thoroughly specify stakeholders' positions. The AHP-derived preferences were used in the achievement function of a goal programming model to examine catch and effort allocation decisions in the Danish commercial fleet.

Decision aids

The importance of stakeholder values is a focus of decision aid MCDM tools, which provide a technique to elucidate preferences over a discrete set of action alternatives and synthesize them into a quantitative ranking of choices. By extracting stakeholders' preferences, decision aids help fully describe management objectives, a prerequisite for avoiding the risk of management failure. Dominant methods include the AHP (Saaty 1980; Zahedi 1986) and **out-ranking methods** (Roy 1991). The aforementioned multiple objective optimization MCDM methods rely on stringent utility theory assumptions such as transitivity of preferences, where $A \succeq B$ and

$B \succeq C \Rightarrow A \succeq C$ ($\succeq$ indicates weak preference of choices), and that an absolute level of a utility function is maximized (see Schoemaker 1982 for an approachable introduction to expected utility theory). AHP on the other hand relies on more relaxed rationality assumptions where decision makers focus on relative value judgments (Linkov *et al.* 2006). AHP breaks down a choice problem into a hierarchy of smaller decisions. Stakeholders indicate their preferences over sub-problem outcomes, for example option A is three times more preferred than option B, and one of several AHP algorithms is used to formulate quantitative ranking of the overall action choices. Due to the focus on trade-offs across stakeholders and objectives, AHP is applicable to fisheries management in cases where discrete management choices need be ranked and acceptability may be more of a goal rather than optimization (e.g. Leung *et al.* 1998).

Similar to AHP, outranking methods provide another means of systematizing stakeholders' preference by conducting pair-wise comparisons amongst choices and eliminating dominated alternatives. Outranking methods use the most relaxed choice theory assumptions by distilling preferences down to two-alternative choices, A is preferred to B, without the need to indicate preference intensity directly in comparisons, and may be appropriate for cases where stakeholders have little experience or limited knowledge about alternative choices (e.g. Kangas *et al.* 2001). No published applications specific to fisheries management are available, however, Hermans *et al.* (2007) used outranking to examine options for ecosystem-level river management. The authors noted that a participatory outranking MCDM analysis was useful for getting stakeholders to think critically about their preferences, contributing to conflict resolution across a diverse group of interests.

Choosing a particular hard MCDM method will ultimately depend on the problem specifics, however some guidelines are presented in Guitouni and Martel (1998).

While the hard MCDM machinery provides an objective decision process that is reproducible and transparent, the data and technical skill costs are high, reducing their usefulness for many natural resource and fisheries management applications (Mendoza and Martins 2006). Less quantitatively intensive soft decision analysis methods are available and have been used in the business world and operations research with success.

Scenario planning and maps

Scenario planning uses in-depth thought exercises to evaluate management options. The process involves identifying a problem and the stakeholders, cooperatively proposing realistic alternative future states of the world, and then ranking management action options by their performance when applied to the proposed future hypothetical scenarios. While quantitative analysis can be included in the evaluation phase, scenario planning does not require it, focusing instead on expert opinion, stakeholder experience and stated preferences (Schoemaker 1995; Peterson *et al.* 2003). Due to its group-participatory nature, a major outcome of the scenario planning process is increased insight into the problem at hand and 'bidirectional' dissemination of information. Experts learn from stakeholders and vice versa by focusing on major uncertainties or risks involved in the management decision, a benefit shared to some degree in many other MCDM methods (Shindler and Cheek 1999; Lahdelma *et al.* 2000).

Similar to scenario planning, **cognitive maps** (see Eden 1992 and articles therein; for a fisheries application see Radomski and Goeman 1996) and **influence diagrams**, also called belief networks, focus on group understanding of a problem (see Shachter 1986; for a fisheries applications see Rieman *et al.* 2001). These are means to describe methodically the workings of a system, for example a linked socioecological fishery, highlighting critical components to making a decision. Participants construct abstract maps of a system, using predefined rules to describe underlying components. In a similar vein, Fig. 1 uses mapping rules to breakdown a generic risk management process into organized stages. Due to their focus on system mechanics, uncertainties and interaction strengths, these techniques are suited for applications under the new paradigm of ecosystem-based fisheries management. While categorized as soft here, quantitative extensions of these techniques are available.

Dynamic risk management: option value and adaptive management

Although most integrated risk assessment and decision analysis call for monitoring and updating (e.g. Analytic Sciences Corporation 1989), conventional plans stop after an action decision has been implemented. Two important techniques stand apart by explicitly incorporating learning after decisions have been taken: **option value analysis**

(Arrow and Fisher 1974; Henry 1974) and **adaptive management** (Walters 1986).

Option value analysis is suggested as a formalization of the **Precautionary Principle** (Farrow 2004). The idea is that learning reduces uncertainty, or generates valuable information, that could inform decisions at a later time and increase net benefits in handling of an asset. Risks of foregone future benefits are managed. Option value encompasses two related forms (Mensink and Requate 2005). **Quasi-option value** analysis focuses on the value from learning in delaying a decision, which is incorporated into a benefits function to be maximized (Arrow and Fisher 1974). **Real options value** additionally incorporates the benefit of maintaining a larger set of choices in the future state of the world, where presumably the decision environment might be better due say to improved technology (Janney and Dess 2004 provided a nontechnical explanation of real options in the context of managerial science). Option value analysis has been used to motivate biodiversity conservation (Humphries *et al.* 1995; Chapin *et al.* 2000; Weikard 2003). In a fisheries context, Fenichel *et al.* (2008) applied option value analysis to evaluate a decision to reintroduce Atlantic salmon in Lake Ontario. Consideration of negative reintroduction risks and the possibility of reducing them by delaying a decision supported a precautionary management programme for low to intermediate discount rates. Obstacles in using option value analysis, common with many complex decision-making techniques, include high data requirements, appropriately defining discount rates which greatly affect the value of delayed benefits, and difficulty in defining an objective function that incorporates diverse stakeholder preferences.

Any management process that updates the plan for the next period based on what has already happened is adaptive management. Formal adaptive management is more specific, seeking to create a plan that improves with experience through time in an efficient manner. The theory of (Walters and Hilborn 1978; Walters 1986) and call for (Costanza *et al.* 1998; CDFG 2008) adaptive management in fisheries has been well established. The process begins with a multi-stakeholder assessment of the resource system, identifying key uncertainties and risks. Analysts determine, usually through modelling, whether or not there is gain to be had by undertaking management experiments to reduce uncertainty, i.e. is the investment in learning worth the effort (e.g. Walters and Pearse 1996)? If there is gain to be had from learning, then a feedback policy is designed which may be passive, where knowledge accumulates by chance under a management plan, or active, where exploratory management, called probing, is undertaken to reduce optimally uncertainty about the workings of a system. An example of probing is a plan to fish deliberately a stock down to low levels to learn about a stock–recruitment relationship. The 'adaptive' component occurs by entering a loop of updating and reevaluating management plans for the next time step as data and experience grow.

By iteratively reinterpreting uncertainties and risks, adaptive feedback policies address a continually changing state of the world. Walters (1986) suggested that given reasonable expectations of the rates of change of structural parameters, learning may be required to maintain a given level of uncertainty, let alone reduce it. As updated risk sets are formulated and managed, hopefully reducing surprises and increasing efficiency, risk management is dynamic vs. static.

Many fisheries agencies employ some form of passive adaptive management, routinely updating harvest regulations and conducting stock assessments. The technical requirements of formal active adaptive management, however, are high and its implementation has been slow. McLain and Lee (1996) and Walters (2007) reviewed obstacles to the use of adaptive management, citing lack of leadership to push adaptive policies through bureaucracies, high institutional costs, and reliance on modelling with associated rigid data requirements as major difficulties. Recently, a more fluid form of adaptive management has seen renewed support as a holistic management process that incorporates resource users and learning into a linked socioecological management process, termed adaptive co-management (Armitage *et al.* 2009).

Management strategy evaluation

Management strategy evaluation is a quantitatively intensive form of decision analysis that incorporates trade-offs between multiple objectives, usually harvest performance (i.e. amount of harvest and year-to-year stability of harvest) vs. stock conservation, with a focus on generating management option performance measures that are robust to uncertainties about the workings of the resource system (Rademeyer *et al.* 2007). Currently, MSE is utilized by several major fishing nations including South Africa (Plaganyi *et al.* 2007) and Australia (Smith *et al.* 1999).

A defining feature of MSE is computer simulation to assess competing hypotheses about population dynamics, as well as to incorporate data and policy implementation uncertainty (for a good introduction to MSE, see *ICES Journal of Marine Science*, 2007, vol. 64, 'Fisheries Management Strategies' special issue). This is achieved with a multistep process: (i) make a hypothesis about the true underlying population dynamics, for example an age-structured model with a given set of parameters, and simulate a population; (ii) make a hypothesis about how data are collected, and simulate data collection by sampling from true data generated by the proposed 'operating model' in part (i); and (iii) estimate the state of the resource using a candidate population assessment methodology and the data from (ii). Performance measures for each management strategy are generated across a range of population dynamics and data hypotheses, and estimation techniques, unveiling those which perform well in the face of uncertainty. The set of management strategies and uncertainty-robust performance outcomes are passed to decision makers who ultimately decide trade-offs amongst objectives, potentially using MCDM techniques mentioned above like decision aids.

Management strategy evaluation invites participation from all stakeholder groups, resulting in improved problem understanding. Furthermore, MSE can incorporate changes in the resource system through time, making management dynamic. Investments to reduce uncertainty around the dynamics of the resource can be incorporated into a management option using 'research-conditional' approaches (Plaganyi *et al.* 2007). Under this strategy, harvest regulations more favourable towards fishing than stock conservation are allowed, contingent upon data collection efforts from fishermen with the idea that long-term gains in understanding of the system will offset any damage to the resource from more aggressive harvest plans. Other forms of MSE, called **management procedure evaluation**, consider policies with adaptive management built into harvest regulation. For example, empirical harvest control rules (Rademeyer *et al.* 2007) prescribe increases in allowable catch when catch per unit effort indices are increasing, and vice versa.

Avoiding risk: the Precautionary Principle

Perhaps, the most straightforward method of managing risk is to avoid it; prevention vs. treatment. Sharing similar components with decision analysis and risk assessment, the general process of risk avoidance involves identifying the risks associated with a proposed action, followed by cost and benefit analysis. If potential costs outweigh the benefits, then decide against the activity.

Risk avoidance opportunities in fisheries management are case-by-case specific. In some instances, risky activities can be spatially or temporally separated. This approach is demonstrated in Waugh *et al.* (2008) who outlined the risk assessment and avoidance process adopted by the Convention for the Conservation of Antarctic Marine Living Resources in relation to pelagic seabird bycatch morality. They show that bycatch mortality has been successfully reduced by separating fishing activity both spatially, by using weighted lines, and temporally by restricting fishing to night and to seasons which avoid high seabird activity. The authors point out that a focus on opportunities to avoid risks circumvents the need to understand the effects of realized risks, which in this case would require data intensive population dynamics modelling to study the effects of bycatch mortality. In other cases, more strict measures may be necessary to avoid risk. Over concern for declining Chinook salmon runs, the North Pacific Fisheries Management Council is considering salmon bycatch caps for the Bering Sea pollock fishery, which would close fishing activity for the season once triggered (NPFMC 2008).

It is usually difficult if not impossible to predict the true costs and benefits of a proposed management action. In these cases, the Precautionary Principle provides a guiding framework for policy creation under risk avoidance. In its pure form, the Principle states that no action should be taken until evidence demonstrates that it is harmless (Foster *et al.* 2000). Taken too literally, it would result in failures to achieve socioeconomic goals of ocean resource management by being overly conservative in foregoing catch and employment. Paradoxically, by being too conservative in avoiding risks, the overall chance of management failure increases and risk management is incomplete. This has led to a level-headed practical implementation of the Principle, called the Precautionary Approach

(Garcia 1994; FAO 1995, 1996). Recognizing the balance between resource use and conservation, the Approach maintains the heart of the Principle, but interprets it in a manner that is open to some risks associated with resource use. It calls for conservative harvest schedules to avoid risks of population collapse or economic extinction (e.g. Restrepo and Powers 1999). In addition, the Approach calls for a shift of the burden of proof away from demonstrating that ongoing activities have unacceptable impacts, to demonstrating that proposed activities will not unacceptably affect socioecological systems (Charles 2002; Gerrodette *et al.* 2002). This is a subtle difference form the pure Principle, but it acknowledges the costs of foregone benefits which if extreme enough may be socioecologically unacceptable themselves. Perry *et al.* (1999) outlined a management process for new and developing fisheries that operationalizes the Precautionary Approach.

Managing risk through transfer

Successful fisheries management requires consideration not only of biological sustainability, but also of economic sustainability for resource users (Hilborn 2006, 2007). Towards that end, insurance policies which transfer risk or the vulnerability to environmental and economic variability away from individual producers provide a business-oriented component to dealing with uncertainty in fishery systems.

Insurance can be defined as a financial arrangement that redistributes the costs of unexpected losses (Dorfman 1978). The key idea is that risk can be transferred to someone who is better able to bear it, moving towards **Pareto efficiency** (Ahsan *et al.* 1982). Pareto efficiency is often used as an economic target for policy, describing a situation where no one can be made better off without making someone else worse off. The transfer of risk to another party comes with a payment for risk-bearing services, an **insurance premium**.

Insurance programmes work by pooling individuals facing losses due to realized risks. The law of large numbers assures that the group loss rate is more certain than any one individual's losses and can be more efficiently managed (Dorfman 1978). From an individual's point of view, his or her losses are spread over the participant pool and a larger uncertain loss from risk exposure is transformed to a smaller certain loss, i.e. a premium payment. With sufficiently structured premiums, the pooled resources can sustain periodic withdrawals from individuals (e.g. Borch 1967; Dorfman 2008). Producers can insure against failures to achieve yield or revenue goals, thereby smoothing out year-to-year income variability, or in the case of more drastic perturbations, to avoid financial ruin, a significant cost to individuals as well as the broader society in which they live (Outreville 1998; Doherty 2000). Furthermore, insurance is a type of risk financing (see below) via a savings programme for individuals who store away revenues, in the form of premiums, for eventual losses to be covered by the insurer.

Risk management through insurance is not widespread in fisheries, however, three forms have been implemented to varying degrees of success: (i) personal health and safety, (ii) asset, and (iii) production and market insurance. The majority of insurance programmes have been individual policies for personal health and safety and for asset protection in developed countries. For example, in 1951 the state of Alaska established the Fishermen's Fund, a mandatory health insurance programme for commercial fishermen funded by licensing fees (State of Alaska 1951). Asset insurance, such as hull protection is typically offered by private firms (e.g. Johnson 1996). Insurance instruments for fisheries in developing countries are less common (Hotta 1999).

Individual insurance policies, where the financial arrangement concerns one insured and an insurance body, are appropriate when loss events are randomly distributed throughout a population. Alternatively, group insurance policies, where the financial arrangement concerns a collection of insureds and an insurance body, provide opportunities for managing risks that simultaneously affect an entire fishery, such as a weak salmon run. Group risk management in fisheries is important due to the large scales at which biological, environmental, and economics processes operate, including aggregated fish populations, large water masses, and market-wide price changes, inter alia.

Little work has been done examining the feasibility of group insurance to protect against production (catch and processed catch) and market (price and revenue) variability in fisheries, however terrestrial crop insurance programmes provide a model (see RMA 2001 for a good overview of these instruments). Notable exceptions are Greenberg *et al.* (2002) and Herrmann *et al.* (2004) who examined the feasibility of crop insurance-type programmes for the Bristol Bay sockeye fishery, a system that has seen booms and busts in catches and prices (also see Mumford *et al.* 2009). Spurred by interest from the United States Department of Agriculture after several economically disastrous years around the turn of the millennium in Bristol Bay, the authors examined the hypothetical dynamics of different policies in terms of premiums and **indemnities**, insurance pay-outs, given historical catch and revenue variability. The results identified significant obstacles to implementing a pooled insurance policy due to inadequate property rights, unstable production trends which make appropriate payout triggers difficult to set, and the difficulty in monitoring the causes of losses, or **perils**.

As highlighted in Greenberg *et al.* (2002) and Herrmann *et al.* (2004), monitoring specific perils is a key practical consideration in fishery applications. How could one assure that a harvester's failure to achieve a catch threshold is due to unpredictable variability, or simply from a lack of harvesting effort? The problem of **moral hazard**, where agents change their behaviour when under an insurance policy as they do not bear the full consequences of their actions, would be substantial. Greenberg *et al.* (2002) coined the term 'fishing the insurance'. Insurance programmes for production risks, however, are not precluded from all fishery applications and may be appropriate for sedentary target species with clearly delineated property rights, such as territorial user rights or area leases in wild harvest or cultivation of shellfish such as clams, oysters, or loco (Gonzalez *et al.* 2006). In these cases, insurance policy regulators have the ability to monitor perils by directly observing the harvested resource as well as producers' treatment of it. The United States Department of Agriculture has implemented pilot programmes for quahog clam growers in Florida, Massachusetts, South Carolina and Virginia, since 1999 (RMA 2008) and most recently for oysters in Louisiana in 2008 (Crop Insurance Systems Inc 2008). While the success of these innovative shellfish insurance programmes is yet unknown, care need be taken to design insurance policies for fishery resources that do not result in revenue subsidies, exacerbating over-capacity issues, but instead sustain resource users through economically catastrophic yield or revenue variability until good times reappear, a narrow tightrope to walk (e.g. Schrank 1998).

Controlling risk: diversification and the portfolio effect

The goal of risk management through diversification is to take advantage of probabilistic properties to both reduce the likelihood and severity of a loss by constructing a bundle of assets, a **portfolio**. The term **asset** is general and can refer to species, fish stocks, income sources, or financial securities, inter alia. Portfolio theory focuses on the selection of assets to create a bundle that provides the greatest expected performance, say catch or annual income, at the least variation about the expected performance (Markowitz 1952; Roy 1952).

Diversification and portfolio theory rely on two phenomena: statistical averaging and correlations amongst portfolio components. Statistical averaging is the effect that a sum of random variables, such as catch value, has lower variance than the individual variables themselves, contributing to portfolio performance stability (Doak *et al.* 1998; Tilman *et al.* 1998). The effect can operate both with statistically independent or correlated assets. The second component of diversification plays out when assets' performances are not independent. Discrepancies in correlations amongst asset returns are exploited to reduce variability about an expected performance (Elton and Gruber 1977, 1995). This is the effect taken advantage of by a farmer who plants a mix of dry- and wet-adapted crops like wheat and peas to stabilize harvest in the face of unpredictable weather (e.g. Miller *et al.* 2002). An important output in portfolio analysis is the **efficiency frontier**, denoting those portfolios with minimum variance at any expected performance level. Portfolios below the efficiency frontier are suboptimal as a better performance can be achieved at the same variance, or the same performance at a lower variance.

Diversification as a risk management strategy arose in the financial literature (Markowitz 1999), but has been recently emerged in natural resource management to study the stabilizing effects of biodiversity (Lehman and Tilman 2000; Figge 2004; Koellner and Schmitz 2006; Tilman *et al.* 2006). van Oostenbrugge *et al.* (2002) examined catch variability in multispecies fisheries in Malaysia, noting that total catch variance is reduced when fishing a bundle of species. Furthermore, it is likely that diversification will be important to maintain ecosystem services in the face of changing climate. Hilborn *et al.* (2003) and Schindler *et al.* ('Population diversity and the portfolio effect in exploited species', unpublished manuscript in review) noted that life history variation across sockeye salmon populations provide a buffering mechanism against environmental variability, resulting in sustained high runs in Bristol Bay, Alaska.

Apart from passive observations on the role of diversification in ecological systems, few attempts have been made to engage actively in portfolio management of fisheries resources. Exceptions include Baldursson and Magnusson (1997) who used portfolio analysis to examine optimal fishing on different age classes of Icelandic cod with a performance metric of net revenues. Sanchirico *et al.* (2008) used portfolio theory to examine alternate ecosystem-level harvesting strategies in Chesapeake Bay, USA, noting that some commercially important stocks negatively covary contemporaneously. By computing mean-variance frontiers, they found that efficiency gains are possible when addressing natural variability at the ecosystem-level. In a similar vein, Larkin *et al.* (2003) computed efficiency frontiers to identify processed seafood product mixes that maximize return for a given risk level in the US Pacific Whiting fishery. Finally, Perruso *et al.* (2005) used portfolio analysis to formulate a model of optimal behaviour for different longline fleets in the Gulf of Mexico and Southwest North Atlantic based on catch and area portfolios. The model was used to examine differential effects of spatial closures across fleets, and to suggest policies that can accommodate different user groups' optimal strategies.

Portfolio theory is more widely applicable as a risk management technique to not only increase efficiency, but also reduce the exposure to both biological and economic variability in fishery systems (Edwards *et al.* 2004). Two areas of applicability are evident. First, the basic tenets of portfolio theory motivate generalization vs. specialization in a variable world, whereas many currently employed fishery regulations result in technological specialization (Whitmarsh 1998). Field work by anthropologists and sociologists has noted the importance of diversifying sources of income as a response to highly variable fish stocks (Ellis 1998; Baelde 2001; Marshall *et al.* 2007; Minnegal and Dwyer 2008). McCay (1981) found evidence that diversified fishing communities in New Jersey show robustness to both ecological and regulatory variability. Similarly, Minnegal and Dwyer (2008) suggested that diversification in a South East Australian fishing community has provided robustness to biological, economic and institutional variability, the latter including specialization-promoting policies of individual transferrable quotas. Hilborn *et al.* (2001) emphasized the social fall out from cod collapse and specialization in Eastern Canada suggesting that policies promoting multi-income fishermen may help prevent such drastic failures of fisheries management.

Second, quantitative portfolio analysis can be further developed in fisheries. Maintaining all stocks in an ecosystem at a single-species maximum sustainable or maximum economic yield is an impossibility due to biological and socioeconomic constraints (Crutchfield 1973; Larkin 1977; May *et al.* 1979). From the point of view of an ecosystem manager, trade-offs between what to include in the harvest portfolio are inevitable, analogous to an investor constrained by a budget. Portfolio analysis can help design harvest policies resulting in lower variance by making trade-offs wisely, taking advantage of discrepancies in stock correlations. Tools to analyse risk exposure when harvesting across species in an ecosystem include **value-at-risk**, a technique of managing probabilistic exposure to maximum portfolio losses (e.g. Holton 2003), and **risk budgeting**, a process of decomposing an aggregate measure of risk into its factor components to identify and manage risk contributors in a portfolio (e.g. Pearson 2002). Furthermore, value-at-risk and risk budgeting present policy outcomes in easily communicated metrics, like the maximum level of biomass loss at a given confidence level associated with a harvest plan or the stocks which contribute most to harvest plan risk.

Portfolio analysis is applicable to a variety of performance metrics in addition to the standard biological measures of harvest, including employment or revenues (Edwards *et al.* 2004). Webby *et al.* (2007) used value-at-risk to analyse outcomes of policies to change water levels on the Mekong River, examining effects on the culturally and economically important Tonle Sap fisheries in Cambodia. The trade-off between water level and fishery resources is summarized into a digestible format for policy makers by computing distributions of expected losses in fishery revenues across different water level policy choices.

As a simple example of the portfolio effect at work, consider the variation in commercial catches from time series of the major salmon runs in Bristol Bay, Alaska. Table 3 presents the coefficient of variation for the five major salmon districts over the

Table 3 Coefficients of variation of annual sockeye harvest from the major commercial fishing districts in Bristol Bay, Alaska, over a short-term (1998–2008) and long-term (1955–2008) period.

	1998–2008 (%)	1955–2008 (%)
Togiak	41.6	81.6
Nushagak	36.7	80.9
Naknek-Kvichak	49.3	80.8
Egegik	40.2	97.4
Ugashik	57.5	101.8
Combined	35.1	68.8

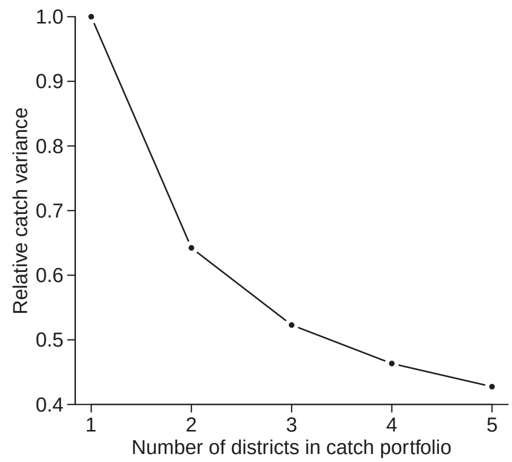

Figure 3 Relative expected variances from catch portfolios with equal investment across assets, i.e. equal harvest proportion from each of one to five fishing districts, for Bristol Bay, Alaska. Variances are relative to the one-district, undiversified, catch portfolio, and are computed using annual sockeye harvest data (1955–2008). Note, the *y*-axis starts at 0.4.

past 10 years and since data collection began in 1955. An agent holding a 'portfolio' of catch from any one river system would experience higher year-to-year variability than a holder of a portfolio diversified (equally) across all districts. To see this, consider the following equation for the variance of portfolio return from Elton and Gruber (1995):

$$\sigma_P^2 = \sum_{i=1}^{n} X_i^2 \sigma_i^2 + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} X_i X_j \sigma_{ij}, \tag{1}$$

where σ_P^2 is the variance of the portfolio performance, n is the number of assets in the portfolio, X_i is the proportion of the total investment budget in asset i, σ_i^2 is the variance of return from asset i, and σ_{ij} is the covariance between the returns from a pair of assets in the portfolio. Note first that if all assets are independent, then the covariance terms drop out and the statistical averaging effect appears: as the number of assets increases, then each of the respective X_i^2 approach very small numbers and portfolio variance approaches zero (alternatively, in the case of equal weighting across independent assets, each $X_i = 1/n$ and the first term can be written as $(1/n)\bar{\sigma}_i^2$, where $\bar{\sigma}_i^2$ is the average variance across all assets in the portfolio; this term approaches zero as n grows large.) If assets are statistically dependent, then pair-wise return covariances can be exploited to reduce overall portfolio variance.

Using Equation (1) and the time series of Bristol Bay district catches from 1955 to 2008, Fig. 3 demonstrates the diversification effect. If an individual or group of individuals could pool their 'investment' over multiple districts, expected catch variance would be reduced by as much as 50% with a fully diversified portfolio.

Controlling risk: price risk management

Price variability is a primary component of revenue variability, a major source of risk for fishery participants and the broader fishing industry. This form of variability is also termed **marketing risk**, where the transformation of production activities to financial reward occurs under uncertainty (RMA 1997). Marketing risk can make operating a business difficult and can negatively affect inter-temporal resource allocation decisions (Larson *et al.* 1998), for example the financing of new fishing gear or processing facilities.

To see the relationship between price and revenue risk, consider the following simple relationship in log space:

$$V(\ln R) = V(\ln(P{\cdot}Q)) = V(\ln P) + V(\ln Q) + 2\mathrm{Cov}(\ln P, \ln Q), \tag{2}$$

where $V()$ is variance, Cov() is covariance, and R, P, and Q, are revenue, price and catch. In cases where production has a strong effect on prices, called an elastic price response, some natural buffering of price variability occurs where low (high) production results in higher (lower) prices, or the covariance term is negative. Natural buffering is not a given, however, as price is a complex function of both endogenous and exogenous factors, such as the supply of substitutes. Local fisheries are often **price takers**, i.e. local catch is too small relative to total market supply to move prices. Figure 4 presents price variability and price–catch correlation information for 135 US fisheries where time series of real prices and catches are available. While a number of stocks have some natural buffering from price–quantity effects, there are a large number of fisheries with little revenue buffering and high price coefficients of variation.

Several price risk management strategies are applicable to fisheries: (i) **marketing timing** strategies, (ii) **forward contracting** and **futures**, and (iii) enterprise integration. Marketing timing strategies involve spreading out the sale of products on cash markets over time, providing a natural buffer against price variability (e.g. Patrick 1992).

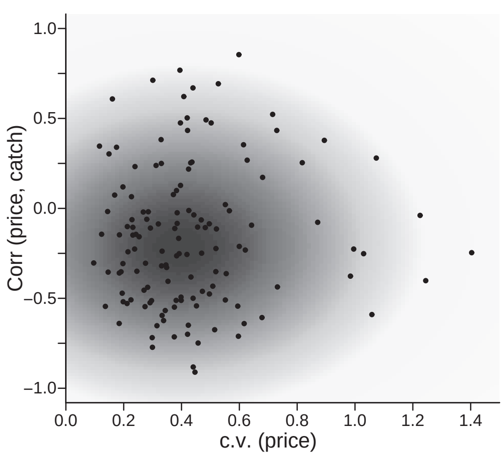

Figure 4 Price variation and revenue buffering characteristics for 135 US fisheries. The *x*-axis dimension is price coefficient of variation, c.v.(price), and the *y*-axis dimension is correlation of price and catch, corr(price,catch). Each fishery is plotted as a point against a density background generated using a kernel smoother. A total of 72% of the fisheries have negative corr(price,catch), indicating some revenue buffering: when catch decreases, price increases and vice versa. Mean c.v.(price) and corr(price,catch) are 0.43 and −0.16, respectively. Fisheries were selected on a basis of data availability, representing those with at least 10 years of price and catch records from the University of British Columbia Sea Around Us Project and the Fisheries Economics Research Unit.

Forwards and futures

Forward contracting and futures are a means for buyers and sellers of fish to remove price uncertainty by locking into an agreement to sell or buy at a given price at a later time. A future is a standardized, tradable contract to deliver agreed upon quantities of graded product at a later date for a specified price. For example, a contract might entail the delivery of 10 tonnes of 3–4 kg head-on gutted superior quality salmon in 6 months time at a price of \$5.00 kg^{-1} (e.g. Fish Pool ASA 2008). They can be used to manage price risk in two ways. First off, future contracts held to delivery provide a means of reducing price uncertainty to zero, however, with some possibility of one side of the exchange not fulfilling their end of the bargain, or **counter party risk**.

Second, futures provide a method of **hedging** price movements in the case where contracts are not held until delivery. Hedging is taking a position in two or more markets such that a loss in one market can be offset by a gain in another (Catlett and Libbin 2007). This works as follows (Fig. 5). Suppose a fish processor in July knows they will sell 50 tonnes of salmon in September to a distributor and would like to lock in a price for the later sale, reducing operating income uncertainty. In July, the processor enters the futures market to sell five futures contracts, each for delivery of 10 tonnes in say December. At the feasible sale time in September, he closes his position by offsetting the futures sold in July by buying five futures contracts for December delivery, and concurrently enters the **spot**, i.e. cash, market by selling the salmon to the distributor. Denoting F and S for futures and spot market prices for a 10-tonne lot of salmon, the difference in price received by the cash sale in July (if it were feasible) vs. a futures hedge is:

$$S_{\text{july}} - [S_{\text{sept.}} + F_{\text{july}} - F_{\text{sept.}}] = (S_{\text{july}} - F_{\text{july}}) - (S_{\text{sept.}} - F_{\text{sept.}}). \quad (3)$$

If the spot and future prices move together, which theoretically they are proposed to do so being based on the same underlying asset value, then price movements are nullified by the hedge and the processor receives the cash price from July (Johnson 1960; Hull 1997).

The processor could also lock in a price more directly through a forward, which is an individual-to-individual customized contract for delivery of a

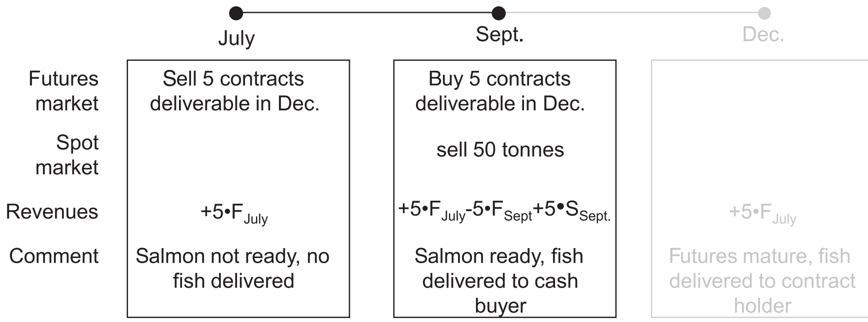

Figure 5 Hypothetical timeline of a processor using a futures hedge to lock in July prices for sale of salmon in September. Corresponding with the explanation in the text, each futures contract is for 10 tonnes of salmon deliverable in December. F_{July} and $F_{\text{Sept.}}$ denote the price of a futures contract as traded on an exchange in the respective month, and $S_{\text{Sept.}}$ denotes the price of a 10-tonne lot of salmon on the September spot (cash) market. Greyed out text denotes events that are not part of the hedge, but would occur if the processor chose not close out the futures sold in July by skipping the actions in the September box.

commodity at a specified price and time. Forward contracts are similar to futures; however, they typically involve actual product delivery and are not standardized. As a result, forwards can involve significant counter party risk. Exchange-traded futures have the advantage of lower counter party risk because of independent transaction oversight from the exchange clearinghouse. In addition, these markets provide price discovery benefits where futures prices provide a benchmark for contracts outside of exchanges (Carlton 1984; Hull 1997; UNCTAD 1998).

Futures and forwards as price risk management tools are primarily suited for large buyers and sellers of fish products, such as processors and marketing cooperatives. Their use has only recently been attempted in fisheries, and significant obstacles exist that are particular to wild capture stocks, including difficulty in storing seafood and product quality heterogeneity (Bergfjord 2007). To date, forward markets for farmed salmon (e.g Fish Pool ASA) and futures markets for farmed seafood including shrimp (Sanders and Manfredo 2002) have been created with varying degrees of success.

Enterprise integration

Enterprise integration takes two forms: vertical and horizontal. **Vertical integration** internalizes different production stages such as catching and processing fish in one operation. By internalizing transactions within an operation, the vertically integrated producer avoids some market transactions and their associated price uncertainty (Coase 1937; Cheung 1983). Direct marketing is one form of vertical integration where a harvester could also process their catch into storable and consumable form for sale at a value-add price (Johnson 2007), including value from branding to distinguishing their product as high quality. **Horizontal integration** entails the consolidation or cooperation of many similar firms at the same stage of production, for example the formation of a marketing cooperative for salmon harvesters (Kitts and Edwards 2003; Knapp 2008). When legally permitted, horizontal integration allows harvesters to manage marketing risk by pooling catches to trade in volume and negotiate prices, as well as to take on some aspects of vertical integration such as product branding.

The price risk management strategies outlined above are particular to fishing industry participants, and less in the realm of the typical manager or regulator. Management policy, however, can constrain the set of price risk management choices available to participants. For example, individual transferrable quotas allowed West Coast US halibut fishermen to spread out their catches over a longer season, choosing their marketing timing to garner better prices and reducing year-to-year price volatility from market gluts (Knapp 1997).

Risk financing: buffers

A risk that is not avoided, transferred or controlled is then retained. Two options exist for retained risks: do nothing, or prepare to bear a possible loss, i.e. to finance the risk, as it is termed in business. Risk financing typically refers to financial preparedness, but it can include any investment to absorb losses from realized risks such as foregoing some catch to maintain conservative harvest limits. Importantly, risks that go unidentified are by default retained. A successfully managed fishery might not identify an oil spill as a risk; however, if shipping occurs in the area, the risk still exists. Given the prevalence of uncertainty and variability in fisheries and the difficulty in identifying all risks that need management, financing is an important strategy to deal with unexpected events, or surprises. In several respects, the Precautionary Approach to fisheries management is a call for risk financing. Accepting the limitations of science in both identifying risks and predicting their effects, management plans designed following the Approach will contain risk financing through conservative resource use limits and biological reserves (see below; Garcia 1994; FAO 1996; Punt 2006).

Buffers are the primary tool to finance risk in fisheries management. They may take several forms: (i) harvest-related buffers that prescribe conservative catch or effort restrictions that can accommodate unexpected biological shocks, (ii) area or temporal closures, or (iii) more directly related to livelihoods, financial reserves. In addition to calling for conservative harvest limits, the FAO's statement of the Precautionary Approach for the management of capture fisheries calls for marine reserves as buffers, quoting 'to limit risks to the resource and the environment, use area closures, which are relatively quick to implement and are easily enforceable (FAO 1996, p. 14).' While their costs and benefits are debated and depend on the performance criteria, such as harvest vs. ecotourism, calls for marine reserves as safeguards against uncertainty in the fisheries science community abound (Clark 1996; Lauck *et al.* 1998; Murray *et al.* 1999; Dayton *et al.* 2000; Stefansson and Rosenberg 2005). Empirical support for the effectiveness of marine reserves in increasing fishery yields is not well established, however there is some preliminary evidence of capacity to buffer against deleterious ecological and human effects by protecting areas of ocean habitat as undisturbed (Roberts *et al.* 2001 but see Tupper *et al.* 2002; Halpern 2003).

Financial buffers provide monetary reserves for fishery participants to weather losses. In some cases, group pay-in to financial reserves is compulsory, a form of forced risk sharing for potential losses similar to involuntary insurance. One example is the state of Alaska's fishermen fund mentioned in the risk transfer section, which provides an emergency reserve for underinsured fishermen who get injured on the job. Other financial buffers include management agency contingency budgets which allow for flexibility in the case of surprise ecosystem developments or fishery losses (Hilborn 1987). Financial buffers are usually administered at the level of a central authority, for example the US Department of Commerce is authorized monetarily aid fisheries in the event of a disaster (where pay-in, by US tax payers, is mandatory), however they could also be used by individuals, fishing communities, or cooperatives.

Summary and conclusions

It is reasonable to expect that conflicts in fisheries management will increase with time as human population grows and seafood demand increases (Pitcher 2008). Calls for the best available science abound (e.g. Article 61 in UNDOALS 1982), which are often answered with calls for more data. Filling data gaps and monitoring are essential to understand the implications of management actions; however, decisions need be made at present. Risk management provides some pragmatic means for coping with variability and navigating trade-offs in ocean resource management.

A wide array of risk management tools that are suitable for fisheries issues is available (Table 2) and some innovative uses have emerged. Opportunities to manage risk are available for all levels of fisheries management, including fishermen who are faced with increasing challenges to maintaining livelihoods. At a broader level, risk management tools will be important for ecosystem-based fisheries management where interactions and trade-offs are a focus. MCDM tools provide means of formulating decisions when considering the multitude of stakeholder interests and ecosystem components involved in an ecosystem-based fisheries management plan. Portfolio theory and the diversification principle provide means of controlling risk when simultaneously managing across 'assets' in the ecosystem. Finally, risk financing and avoidance help provide a margin of error given the high levels of uncertainty and variability typical with ocean ecosystems.

While there are opportunities to expand risk management in fisheries, there are also challenges.

Proposed management plans need to pass cost–benefit analysis to determine whether outcomes are worth implementation costs, which include foregone opportunities. In such an evaluation, the costs of risk management can be difficult to justify as benefits are often in avoided losses: it is difficult to tell if success occurs because risks were addressed, or because they failed to materialize simply due to chance. In addition, risk management tools have been developed in a wide range of disciplines which are not commonly explored by fisheries scientists and managers, including operations research, finance, and engineering. Implementation will probably require multi-disciplinary cooperation. In concert with solutions to properly align resource user incentives (Grafton *et al.* 2006), risk management promises to play an integral role in the new paradigm of fisheries management, where instead of inexhaustibility (Huxley 1884), uncertainty, scarcity and trade-offs rule.

Acknowledgements

This work was supported by a National Science Foundation Graduate Research Fellowship. I thank Ray Hilborn, Trevor Branch and two anonymous referees for helpful comments that improved this article. Synthesized data for Fig. 3 were provided by the University of Washington Alaska Salmon Program funded by the Gordon and Betty Moore Foundation, the Pew Institute and the National Science Foundation. Data for Fig. 4 were provided by R. Watson and R. Sumaila from the Pew-funded Sea Around Us Project at the University of British Columbia.

References

Ahsan, S.M., Ali, A.A.G. and Kurian, N.J. (1982) Toward a theory of agricultural insurance. *American Journal of Agricultural Economics* **64**, 520–529.

Analytic Sciences Corporation (1989) *Risk Management: Concepts and Guidance*. U.S. Defense Systems Management College, No. ADA214342, Fort Belvoir, 244 pp.

Armitage, D.R., Plummer, R., Berkes, F. *et al.* (2009) Adaptive co-management for social-ecological complexity. *Frontiers in Ecology and the Environment* **7**, 95–102.

Arrow, K.J. and Fisher, A.C. (1974) Environmental preservation, uncertainty, and irreversibility. *The Quarterly Journal of Economics* **88**, 312–319.

Athearn, J.L. (1971) What is risk? *The Journal of Risk and Insurance* **38**, 639–645.

Baelde, P. (2001) Fishers' description of changes in fishing gear and fishing practices in the Australian South East Trawl Fishery. *Marine and Freshwater Research* **52**, 411–417.

Baldursson, F.M. and Magnusson, G. (1997) Portfolio fishing. *Scandinavian Journal of Economics* **99**, 389–403.

Belton, V. and Stewart, T.J. (2002) *Multiple Criteria Decision Analysis: An Integrated Approach*. Kluwer Academic, Boston.

Bergfjord, O.J. (2007) Is there a future for salmon futures? An analysis of the prospects of a potential futures market for salmon. *Aquaculture Economics and Management* **11**, 113–132.

Borch, K. (1967) The economic theory of insurance. *The Astin Bulletin* **4**, 252–264.

Brachinger, H.W. and Weber, M. (1997) Risk as a primitive: a survey of measures of perceived risk. *OR Spektrum* **19**, 235–250.

Carlton, D. (1984) Futures markets: their purpose, their history, their growth, their successes and failures. *Journal of Futures Markets* **4**, 237–271.

Catlett, L.B. and Libbin, J.D. (2007) *Risk Management in Agriculture: A Guide to Futures, Options, and Swaps*. Thomson Delmar Learning, Clifton Park.

CDFG (California Department of Fish and Game) (2008) *California Marine Life Protection Act: Master Plan for Marine Protected Areas*. CDFG, Revised Draft January 2008, Sacramento, 110 pp.

Chapin, F.S., Zavaleta, E.S., Eviner, V.T. *et al.* (2000) Consequences of changing biodiversity. *Nature* **405**, 234–242.

Charles, A.T. (1998) Living with uncertainty in fisheries: analytical methods, management priorities and the Canadian groundfishery experience. *Fisheries Research* **37**, 37–50.

Charles, A.T. (2002) The precautionary approach and 'burden of proof' challenges in fishery management. *Bulletin of Marine Science* **70**, 683–694.

Cheung, S.N.S. (1983) The contractual nature of the firm. *Journal of Law and Economics* **26**, 1–21.

Clark, C.W. (1990) *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*, 2nd edn. Wiley, New York.

Clark, C.W. (1996) Marine reserves and the precautionary management of fisheries. *Ecological Applications* **6**, 369–370.

Coase, R.H. (1937) The nature of the firm. *Economica* **16**, 386–405.

Costanza, R., Andrade, F., Antunes, P. *et al.* (1998) Principles for sustainable governance of the oceans. *Science* **281**, 198–199.

Crockford, N. (1991) *Risk Management*. Witherby, London.

Crop Insurance Systems Inc. (2008) *Oyster Insurance Program*. The Gulf Oyster Industry Council Report. Crop Insurance Systems Inc., Olathe, 6 pp.

Crutchfield, J.A. (1973) Economic and political objectives in fishery management. *Transactions of the American Fisheries Society* **102**, 481–491.

Dayton, P.K., Sala, E., Tegner, M.J. and Thrush, S. (2000) Marine reserves: parks, baselines, and fishery enhancement. *Bulletin of Marine Science* **66**, 617–634.

Doak, D.F., Bigger, D., Harding, E.K., Marvier, M.A., O'Malley, R.E. and Thomson, D. (1998) The statistical inevitability of stability-diversity relationships in community ecology. *The American Naturalist* **151**, 264–276.

Doherty, N. (2000) Innovation in corporate risk management: the case of catastrophe risk. In: *Handbook of Insurance* (ed. G. Dionne). Kluwer Academic, Boston, pp. 503–539.

Dorfman, M.S. (1978) *Introduction to Insurance*. Prentice Hall, Englewood Cliffs.

Dorfman, M.S. (2008) *Introduction to Risk Management and Insurance*. Prentice Hall, Upper Saddle River.

Eden, C. (1992) On the nature of cognitive maps. *Journal of Management Studies* **29**, 261–265.

Edwards, S.F., Link, J.S. and Rountree, B.P. (2004) Portfolio management of wild fish stocks. *Ecological Economics* **49**, 317–329.

Ellis, F. (1998) Household strategies and rural livelihood diversification. *Journal of Development Studies* **35**, 1–38.

Elton, E.J. and Gruber, M.J. (1977) Risk reduction and portfolio size: an analytical solution. *The Journal of Business* **50**, 415–437.

Elton, E.J. and Gruber, M.J. (1995) *Modern Portfolio Theory and Investment Analysis*. Wiley, New York.

FAO (Food and Agricultural Organization of the United Nations) (1995) *Code of Conduct for Responsible Fisheries*. FAO, Rome, 41 pp.

FAO (1996) *Precautionary Approach to Capture Fisheries and Species Introductions*. FAO Technial Guidelines for Responsible Fisheries, No. 2. FAO, Rome, 54 pp.

Farrow, S. (2004) Using risk assessment, benefit-cost analysis, and real options to implement a precautionary principle. *Risk Analysis* **24**, 727–735.

Fenichel, E.P., Tsao, J.I., Jones, M.L. and Hickling, G.J. (2008) Real options for precautionary fisheries management. *Fish and Fisheries* **9**, 121–137.

Figge, F. (2004) Bio-folio: applying portfolio theory to biodiversity. *Biodiversity and Conservation* **13**, 827–849.

Fish Pool ASA (2008) *Appendix 1 to Fish Pool Rule Book: Product Specifications and Trading Schedule for Trading at Fish Pool Markets*. Fish Pool ASA, Bergen, 5 pp.

Foster, K.R., Vecchia, P. and Repacholi, M.H. (2000) Risk Management: science and the Precautionary Principle. *Science* **288**, 979–981.

Francis, R. and Shotton, R. (1997) ''Risk'' in fisheries management: a review. *Canadian Journal of Fisheries and Aquatic Sciences* **54**, 1699–1715.

Garcia, S.M. (1994) The precautionary principle: its implications in capture fisheries management. *Ocean and Coastal Management* **22**, 99–125.

Gerrodette, T., Dayton, P.K., Macinko, S. and Fogarty, M.J. (2002) Precautionary management of marine fisheries: moving beyond burden of proof. *Bulletin of Marine Science* **70**, 657–668.

Gonzalez, J., Stotz, W., Garrido, J. *et al.* (2006) The Chilean TURF system: how is it performing in the case of the loco fishery? *Bulletin of Marine Science* **78**, 499–527.

Grafton, R.Q., Arnason, R., Bjorndal, T. *et al.* (2006) Incentive-based approaches to sustainable fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* **63**, 699–710.

Greenberg, J., Herrmann, M., Geier, H. and Hamel, C. (2002) *Wild Salmon Risk Management in Bristol Bay, Alaska*. Final report to the U.S. Department of Agriculture. Risk Management Agency, Washington D.C., 385 pp.

Guitouni, A. and Martel, J.-M. (1998) Tentative guidelines to help choosing an appropriate MCDA method. *European Journal of Operational Research* **109**, 501–521.

Haimes, Y.Y. (1998) *Risk Modeling, Assessment, and Management*. Wiley, New York.

Halpern, B.S. (2003) The impact of marine reserves: do reserves work and does reserve size matter? *Ecological Applications* **13**, S117–S137.

Hanna, S.S. (1997) The new frontier of American fisheries governance. *Ecological Economics* **20**, 221–233.

Harwood, J. (2000) Risk assessment and decision analysis in conservation. *Biological Conservation* **95**, 219–226.

Harwood, J. and Stokes, K. (2003) Coping with uncertainty in ecological advice: lessons from fisheries. *Trends in Ecology & Evolution* **18**, 617–622.

Henry, C. (1974) Option values in the economics of irreplaceable assets. *Review of Economic Studies* **41**, 89–104.

Herath, G. and Prato, T. (2006) *Using Multi-Criteria Decision Analysis in Natural Resource Management*. Ashgate Publishing, Burlington.

Hermans, C., Erickson, J., Noordewier, T., Sheldon, A. and Kline, M. (2007) Collaborative environmental planning in river management: an application of multicriteria decision analysis in the White River Watershed in Vermont. *Journal of Environmental Management* **84**, 534–546.

Herrmann, M., Greenberg, J., Hamel, C. and Geier, H. (2004) Extending federal crop insurance programs to commercial fisheries: the case of Bristol Bay, Alaska, Sockeye salmon. *North American Journal of Fisheries Management* **24**, 352–366.

Hilborn, R. (1987) Living with uncertainty in resource management. *North American Journal of Fisheries Management* **7**, 1–5.

Hilborn, R. (2006) Fisheries success and failure: the case of the Bristol Bay salmon fishery. *Bulletin of Marine Science* **78**, 487–498.

Hilborn, R. (2007) Moving to sustainability by learning from successful fisheries. *Ambio* **36**, 296–303.

Hilborn, R. and Walters, C.J. (1977) Differing goals of salmon management on the Skeena River. *Journal of the Fisheries Research Board of Canada* **34**, 64–72.

Hilborn, R., Maguire, J.J., Parma, A.M. and Rosenberg, A.A. (2001) The precautionary approach and risk management: can they increase the probability of successes in fishery management? *Canadian Journal of Fisheries and Aquatic Sciences* **58**, 99–107.

Hilborn, R., Quinn, T.P., Schindler, D.E. and Rogers, D.E. (2003) Biocomplexity and fisheries sustainability. *Proceedings of the National Academy of Sciences of the United States of America* **100**, 6564–6568.

Holton, G.A. (2003) *Value-at-Risk: Theory and Practice*. Academic Press, Boston.

Hotta, M. (1999) *Fisheries Insurance Programmes in Asia: Experiences, Practices and Principles*. Food and Agricultural Organization Fisheries Circular, No. 948, FAO, Rome, 58 pp.

Hull, J.C. (1997) *Options, Futures, and Other Derivatives*. Prentice-Hall, Upper Saddle River.

Humphries, C.J., Williams, P.H. and Wright, R.I.V. (1995) Measuring biodiversity value for conservation. *Annual Review of Ecology and Systematics* **26**, 93–111.

Hutchings, J.A. and Myers, R.A. (1994) What can be learned from the collapse of a renewable resource – Atlantic cod, Gadus-Morhua, of Newfoundland and Labrador. *Canadian Journal of Fisheries and Aquatic Sciences* **51**, 2126–2146.

Huxley, T.H. (1884) Inaugural address. *Fisheries Exhibition Literature* **4**, 1–22.

Janney, J.J. and Dess, G.G. (2004) Can real-options analysis improve decision-making? Promises and pitfalls. *Academy of Management Executive* **18**, 60–75.

Johnson, L.L. (1960) The theory of hedging and speculation in commodity futures. *The Review of Economic Studies* **27**, 139–151.

Johnson, T. (1996) *Fishing Vessel Insurance: How Much Is Enough?* Alaska Sea Grant Advisory Program, No. 34, Alaska Sea Grant, Fairbanks, 8 pp.

Johnson, T. (2007) *Fishermen's Direct Marketing Manual*. Alaska Sea Grant Marine Advisory Program, No. WSG-AS-03 03 MAB-53, Alaska Sea Grant, Fairbanks, 96 pp.

Kangas, A.S. and Kangas, J. (2004) Probability, possibility and evidence: approaches to consider risk and uncertainty in forestry decision analysis. *Forest Policy and Economics* **6**, 169–188.

Kangas, A.S., Kangas, J. and Pykäläinen, J. (2001) Outranking methods as tools in strategic natural resources planning. *Silva Fennica* **35**, 215–227.

Kitts, A.W. and Edwards, S.F. (2003) Cooperatives in US fisheries: realizing the potential of the fishermen's collective marketing act. *Marine Policy* **27**, 357–366.

Kjaersgaard, J. (2007) Multiple criteria decision making in fisheries management: experiences and implications. *Acta Agriculturae Scandinavica, Section C – Economy* **4**, 49–64.

Kjaersgaard, J., Andersen, J. and Mathiesen, C. (2007) Multiple objectives and perceptions of optimal management: the Danish industrial fishery in the North Sea. *European Review of Agricultural Economics* **34**, 181–208.

Knapp, G. (1997) Initial effects of the Alaska halibut IFQ program: survey comments of Alaska fishermen. *Marine Resource Economics* **12**, 239–248.

Knapp, G. (2008) The Chignik salmon cooperative. In: *Case Studies in Fisheries Self-Governance* (eds R. Townsend, R. Shotton and H. Uchida). Food and Agricultural Organization, Rome, pp. 335–348.

Koellner, T. and Schmitz, O.J. (2006) Biodiversity, ecosystem function, and investment risk. *BioScience* **56**, 977–985.

Lahdelma, R., Salminen, P. and Hokkanen, J. (2000) Using multicriteria methods in environmental planning and management. *Environmental Management* **26**, 595–605.

Lane, D.E. and Stephenson, R.L. (1998) A framework for risk analysis in fisheries decision-making. *ICES Journal of Marine Science* **55**, 1–13.

Larkin, P.A. (1977) An epitaph for the concept of maximum sustained yield. *Transactions of the American Fisheries Society* **106**, 1–11.

Larkin, S., Sylvia, G. and Tuininga, C. (2003) Portfolio analysis for optimal seafood product diversification and resource management. *Journal of Agricultural and Resource Economics* **28**, 252–271.

Larson, D.F., Varangis, P. and Yabuki, N. (1998) *Commodity Risk Management and Development*. The World Bank, No. 1963, Washington D.C., 46 pp.

Lauck, T., Clark, C.W., Mangel, M. and Munro, G.R. (1998) Implementing the precautionary principle in fisheries management through marine reserves. *Ecological Applications* **8**, S72–S78.

Leal, D.R. (2008) A fishermen's agreement and co-op in Yaquina Bay roe herring. In: *Case Studies in Fisheries Self-Governance* (eds R. Townsend, R. Shotton and H. Uchida). Food and Agricultural Organization, Rome, pp. 415–423.

Lee, S.M. and Olson, D.L. (1999) Goal programming. In: *Multicriteria Decision Making: Advances in MCDM Models, Algorithms, Theory, and Applications* (eds T. Gal, T.J. Stewart and T. Hanne). Kluwer Academic, Boston, pp. 81–833.

Lehman, C.L. and Tilman, D. (2000) Biodiversity, stability, and productivity in competitive communities. *The American Naturalist* **156**, 534–552.

Leung, P. (2006) Multiple-criteria decision making (MCDM) applications in fishery management. *International Journal of Environmental Technology and Management* **6**, 96–100.

Leung, P., Muraoka, J., Nakamoto, S.T. and Pooley, S. (1998) Evaluating fisheries management options in Hawaii using analytic hierarchy process (AHP). *Fisheries Research* **36**, 171–183.

Linkov, I., Satterstrom, F.K., Kiker, G., Batchelor, C., Bridges, T. and Ferguson, E. (2006) From comparative risk assessment to multi-criteria decision analysis and adaptive management: recent developments and applications. *Environment International* **32**, 1072–1093.

Ludwig, D., Hilborn, R. and Waters, C. (1993) Uncertainty, resource exploitation, and conservation: lessons from history. *Science* **260**, 17–36.

Mardle, S. and Pascoe, S. (1999) A review of applications of multiple-criteria decision-making techniques to fisheries. *Marine Resource Economics* **14**, 41–63.

Mardle, S., Pascoe, S., Tamiz, M. and Jones, D. (2000) Resource allocation in the North Sea demersal fisheries: a goal programming approach. *Annals of Operations Research* **94**, 321–342.

Markowitz, H. (1952) Portfolio selection. *The Journal of Finance* **7**, 77–91.

Markowitz, H.M. (1999) The early history of portfolio theory: 1600-1960. *Financial Analysts Journal* **55**, 5–16.

Marshall, N.A., Fenton, D.M., Marshall, P.A. and Sutton, S.G. (2007) How resource dependency can influence social resilience within a primary resource industry. *Rural Sociology* **72**, 359–390.

May, R.M., Beddington, J.R., Clark, C.W., Holt, S.J. and Laws, R.M. (1979) Management of multispecies fisheries. *Science* **205**, 267–277.

McCay, B.J. (1981) Optimal foragers or political actors? Ecological analyses of a New-Jersey fishery. *American Ethnologist* **8**, 356–382.

McLain, R.J. and Lee, R.G. (1996) Adaptive management: promises and pitfalls. *Environmental Management* **20**, 437–448.

Mendoza, G.A. and Martins, H. (2006) Multi-criteria decision analysis in natural resource management: a critical review of methods and new modeling paradigms. *Forest Ecology and Management* **230**, 1–22.

Mensink, P. and Requate, T. (2005) The Dixit-Pindyck and the Arrow-Fisher-Hanemann-Henry option values are not equivalent: a note on Fisher (2000). *Resource and Energy Economics* **27**, 83–88.

Miller, P.R., McConkey, B.G., Clayton, G.W. *et al.* (2002) Pulse crop adaptation in the Northern Great Plains. *Agronomy Journal* **94**, 261–272.

Minnegal, M. and Dwyer, P.D. (2008) Managing risk, resisting management: stability and diversity in a southern Australian fishing fleet. *Human Organization* **67**, 97–108.

Mumford, J.D., Leach, A.W., Levontin, P. and Kell, L.T. (2009) Insurance mechanisms to mediate economic risks in marine fisheries. *ICES Journal of Marine Science* **66**, 950–959.

Murray, S.N., Ambrose, R.F., Bohnsack, J.A. *et al.* (1999) No-take reserve networks: sustaining fishery populations and marine ecosystems. *Fisheries* **24**, 11–25.

Naish, K.A., Taylor, J.E., Levin, P.S. *et al.* (2008) An evaluation of the effects of conservation and fishery enhancement hatcheries on wild populations of salmon. *Advances in Marine Biology* **53**, 61–194.

NOAA (National Oceanic and Atmospheric Administration) (1997) *Fisheries Strategic Plan*. NOAA, May 1997 Draft, Washington D.C., 48 pp.

NPFMC (North Pacific Fisheries Management Council) (2008) *Bering Sea Chinook Salmon Bycatch Management Draft Environmental Impact Statement*. NOAA, December 2008 Draft, Anchorage, 839 pp.

van Oostenbrugge, J.A.E., Bakker, E.J., van Densen, W.L.T., Machiels, M.A.M. and van Zwieten, P.A.M. (2002) Characterizing catch variability in a multispecies fishery: implications for fishery management. *Canadian Journal of Fisheries and Aquatic Sciences* **59**, 1032–1043.

Outreville, J.F. (1998) *Theory and Practice of Insurance*. Kluwer Academic, Boston.

Pascoe, S. and Mardle, S. (2001) Optimal fleet size in the English Channel: a multi-objective programming approach. *European Review of Agricultural Economics* **28**, 161–185.

Patrick, G.F. (1992) *Managing Risk in Agriculture*. Purdue University Cooperative Extension Service, No. NCR-406, Purdue University, West Lafayette, 30 pp.

Pearson, N.D. (2002) *Risk Budgeting: Portfolio Problem Solving with Value-at-Risk*. Wiley, New York.

Perruso, L., Weldon, R.N. and Larkin, S.L. (2005) Predicting optimal targeting Strategies in multispecies fisheries: a portfolio approach. *Marine Resource Economics* **20**, 25–45.

Perry, R.I., Walters, C.J. and Boutillier, J.A. (1999) A framework for providing scientific advice for the management of new and developing invertebrate fisheries. *Reviews in Fish Biology and Fisheries* **9**, 125–150.

Peterson, G.D., Cumming, G.S. and Carpenter, S.R. (2003) Scenario planning: a tool for conservation in an uncertain world. *Conservation Biology* **17**, 358–366.

Pitcher, T.J. (2008) The sea ahead: challenges to marine biology from seafood sustainability. *Hydrobiologia* **606**, 161–185.

Plaganyi, E.E., Rademeyer, R.A., Butterworth, D.S., Cunningham, C.L. and Johnston, S.J. (2007) Making management procedures operational: innovations implemented in South Africa. *ICES Journal of Marine Science* **64**, 626–632.

Punt, A.E. (2006) The FAO precautionary approach after almost 10 years: have we progressed towards implementing simulation-tested feedback-control management systems for fisheries management? *Natural Resource Modeling* **19**, 441–464.

Punt, A.E. and Hilborn, R. (1997) Fisheries stock assessment and decision analysis: the Bayesian approach. *Reviews in Fish Biology and Fisheries* **7**, 35–63.

Rademeyer, R.A., Plaganyi, E.E. and Butterworth, D.S. (2007) Tips and tricks in designing management procedures. *ICES Journal of Marine Science* **64**, 618–625.

Radomski, P.J. and Goeman, T.J. (1996) Decision making and modeling in freshwater sport-fisheries management. *Fisheries* **21**, 14–21.

Restrepo, V.R. and Powers, J.E. (1999) Precautionary control rules in U.S. fisheries management: specification and performance. *ICES Journal of Marine Science* **56**, 846–852.

Rieman, B., Peterson, J.T., Clayton, J. *et al.* (2001) Evaluation of potential effects of federal land management alternatives on trends of salmonids and their habitats in the interior Columbia River basin. *Forest Ecology and Management* **153**, 43–62.

RMA (Risk Management Agency) (1997) *Introduction to Risk Management. Understanding Agricultural Risks: Production, Marketing, Financial, Legal, Human Resources*. United States Department of Agriculture, Revised 1997 Draft, RMA, Washington D.C., 20 pp.

RMA (2001) *Crop Insurance Program Models*. United States Department of Agriculture, Draft Report, RMA, Washington D.C., 39 pp.

RMA (2008) *Culitvated Clam Pilot Crop Insurance Underwriting Guide*. United States Department of Agriculture, No. FCIC-24100 (08-2007), RMA, Washington D.C., 45 pp.

Roberts, C.M., Bohnsack, J.A., Gell, F., Hawkins, J.P. and Goodridge, R. (2001) Effects of marine reserves on adjacent fisheries. *Science* **294**, 1920–1923.

Rosenberg, A.A. and Restrepo, V.R. (1994) Uncertainty and risk-evaluation in stock assessment advice for U.S. marine fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* **51**, 2715–2720.

Rowe, W.D. (1994) Understanding uncertainty. *Risk Analysis* **14**, 743–750.

Roy, A.D. (1952) Safety first and the holding of assets. *Econometrica* **20**, 431–449.

Roy, B. (1991) The outranking approach and the foundations of ELECTRE methods. *Theory and Decision* **31**, 49–73.

Saaty, T.L. (1980) *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. McGraw-Hill International, New York.

Sanchirico, J.N., Smith, M.D. and Lipton, D.W. (2008) An empirical approach to ecosystem-based fishery management. *Ecological Economics* **64**, 586–596.

Sanders, D.R. and Manfredo, M.R. (2002) The white shrimp futures market: lessons in contract design and marketing. *Agribusiness* **18**, 505–522.

Schoemaker, P.J.H. (1982) The expected utility model: its variants, purposes, evidence and limitations. *Journal of Economic Literature* **20**, 529–563.

Schoemaker, P.J.H. (1995) Scenario planning: a tool for strategic thinking. *Sloan Management Review* **36**, 25–40.

Schrank, W.E. (1998) The failure of Canadian seasonal fishermen's unemployment insurance reform during the 1960s and 1970s. *Marine Policy* **22**, 67–81.

Schrank, W.E. (2005) The Newfoundland fishery: ten years after the moratorium. *Marine Policy* **29**, 407–420.

Shachter, R.D. (1986) Evaluating influence diagrams. *Operations Research* **34**, 871–882.

Shindler, B. and Cheek, K.A. (1999) Integrating citizens in adaptive management: a propositional analysis. *Conservation Ecology* **3**, 9. Available at: http://www.ecologyandsociety.org/vol3/iss1/art9/ (last accessed 21 April 2010).

Sissenwine, M. (1984) The uncertain environment of fishery scientists and managers. *Marine Resource Economics* **1**, 1–30.

Slovic, P., Fischhoff, B. and Lichtenstein, S. (2000) Congitive processes and societal risk taking. In: *The Perception of Risk* (ed. P. Slovic). Earthscan Publications, London, pp. 32–50.

Smith, A.D.M., Sainsbury, K.J. and Stevens, R.A. (1999) Implementing effective fisheries-management systems: 006Danagement strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science* **56**, 967–979.

State of Alaska (1951) *Fishermen's Fund*. Alaska Administrative Code 8 AAC 055.010. State of Alaska, Juneau.

Stefansson, G. and Rosenberg, A.A. (2005) Combining control measures for more effective management of fisheries under uncertainty: quotas, effort limitation and protected areas. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 133–146.

Tilman, D., Lehman, C.L. and Bristow, C.E. (1998) Diversity-stability relationships: statistical inevitability or ecological consequence? *The American Naturalist* **151**, 277–282.

Tilman, D., Reich, P.B. and Knops, J.M.H. (2006) Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature* **441**, 629–632.

Tupper, M.H., Wickstrom, K., Hilborn, R. *et al.* (2002) Marine reserves and fisheries management. *Science* **295**, 1233–1235.

UNCTAD (United Nations Conference on Trade and Development) (1998) *A Survey of Commodity Risk Management Instruments*. UNCTAD, COM/15/Rev. 2, Geneva, 59 pp.

UNDOALS (United Nations Division for Ocean Affairs and the Law of the Sea) (1982) *United Nations Convention on the Law of the Sea*. UNDOALS, New York, 202 pp.

USDC (U.S. Department of Commerce) (2007) *Magnuson-Stevens Fishery Conservation and Management Act*. USDC, Amended through January 2007, Washington D.C., 178 pp.

Walters, C.J. (1986) *Adaptive Management of Renewable Resources*. Macmillan, New York.

Walters, C.J. (2007) Is adaptive management helping to solve fisheries problems? *Ambio* **36**, 304–307.

Walters, C.J. and Hilborn, R. (1978) Ecological optimization and adaptive management. *Annual Review of Ecology and Systematics* **9**, 157–188.

Walters, C.J. and Maguire, J.J. (1996) Lessons for stock assessment from the northern cod collapse. *Reviews in Fish Biology and Fisheries* **6**, 125–137.

Walters, C.J. and Pearse, P.H. (1996) Stock information requirements for quota management systems in com-

mercial fisheries. *Reviews in Fish Biology and Fisheries* **6**, 21–42.
Waugh, S.M., Baker, G.B., Gales, R. and Croxall, J.P. (2008) CCAMLR process of risk assessment to minimise the effects of longline fishing mortality on seabirds. *Marine Policy* **32**, 442–454.
Webby, R.B., Adamson, P.T., Boland, J., Howlett, P.G., Metcalfe, A.V. and Piantadosi, J. (2007) The Mekong-applications of value at risk (VAR) and conditional value at risk (CVAR) simulation to the benefits, costs and consequences of water resources development in a large river basin. *Ecological Modelling* **201**, 89–96.
Weeks, H. and Berkeley, S. (2000) Uncertainty and precautionary management of marine fisheries: can the old methods fit the new mandates? *Fisheries* **25**, 6–15.
Weikard, H.-P. (2003) On the quasi-option value of biodiversity and conservation. In: *Risk and Uncertainty in Environmental and Natural Resource Economics* (eds J. Wesseler, H.-P. Weikard and R.D. Weaver). Edward Elgar, Northampton, pp. 23–37.
Whitmarsh, D.J. (1998) The fisheries treadmill. *Land Economics* **74**, 422–427.
Zahedi, F. (1986) The analytic hierarchy process-a survey of the method and its applications. *Interfaces* **16**, 96–108.

Appendix: glossary of terms

The following definitions are summarized by the author and correspond with bolded terms in the text:

adaptive management: a management process that updates the plan for the next period based on what has already happened.

analytic hierarchy process: a decision aid technique which breaks a complex problem into a series of smaller sub-problems where participants provide intensity of preferences over outcomes.

asset: something of value partially or fully controlled by an individual or organization.

buffer: a form of risk financing, resources set aside as a reserve to absorb surprise losses.

cognitive map: a soft multicriteria decision-making tool, a technique to describe the workings of a complex system by constructing abstract maps for use in decision making.

counter party risk: possibility of a party not fulfilling their side of a contract.

decision aid: a class of hard multicriteria decision-making tools, algorithms for digesting stakeholder preferences into policy rankings.

decision analysis: consider both quantitative and qualitative data to select a plan of action in the face of multiple and conflicting objectives.

efficiency frontier: from investment theory, the set of feasible portfolios offering the greatest expected return at the lowest expected variance.

forward contract: a customized contract for delivery of a commodity at a specified price and time; contrary to futures, these are not standardized and are not usually traded.

futures contract: a standardized, tradable contract for delivery of a graded commodity at a specified time and price.

generating method: sensitivity analysis in multiple objective optimization applications by varying objective preference weights.

goal programming: multiple objective optimization technique where the objective function minimizes deviations from performance goals.

hedging: taking a position in two or more markets such that a loss in one market can be offset by a gain in another.

horizontal integration: consolidation or cooperation of multiple firms at the same stage of production.

indemnity: payout from an insurance policy.

influence diagram: a soft multicriteria decision-making tool, a technique to describe the workings of a complex system by constructing abstract maps for use in decision making.

insurance: a financial arrangement that redistributes the costs of unexpected losses.

insurance premium: a payment for risk-bearing services in an insurance arrangement.

management procedure evaluation: analogous to management strategy evaluation, but focused on feedback policies called harvest control rules.

management strategy evaluation: a method of decision analysis specific to fisheries management, uncertainty-robust management options are proposed using computer simulation to incorporate model, data and implementation uncertainty into the evaluation of management option performance.

marketing risk: the transformation of production activities to financial reward occurs under uncertainty.

marketing timing strategy: a strategy to cope with price variability by spreading out sales through time.

moral hazard: a party changes behaviour when under an insurance policy because they do not bear the full consequences of their actions.

multi-attribute decision tool: an optimization technique analogous to multi-objective utility maximization but with a discrete set of choices to be evaluated.

multicriteria decision making: a broad class of techniques to evaluate multiple facets of a complex problem in order to make a decision.

multiple objective optimization: a class of hard multicriteria decision-making tools that use mathematical optimization of a composite objective function to evaluate choices.

multi-objective utility maximization: a multiple objective optimization technique where the objective function maximizes combined benefits to evaluate choices; choices are continuous, e.g. % harvest.

option value analysis: analysis of an irreversible decision that incorporates the value of learning in delaying a choice; techniques include **quasi-option value** analysis, where value of information is a focus, and **real option**s analysis where maintaining a set of choices is a focus.

out-ranking method: decision aid technique, an algorithm to break a complex decision into smaller sub-problems where participants indicate pair-wise preference over outcomes.

Pareto efficiency: a situation where no one can be made better off without making someone else worse off.

peril: a term used in insurance, the cause of a loss.

portfolio: a bundle of assets.

Precautionary Approach: the practical interpretation of this Precautionary Principle, allowing for some level of acceptable risk in evaluating potential actions.

Precautionary Principle: a philosophy that no action should be taken until proved harmless.

price taker: a producer whose supply of a good is too small relative to market supply to move price, i.e. without market power.

realized risk: an adverse outcome occurs as result of a deviation from an expectation.

risk: a chance of adverse effects from deviations from expectations.

risk budgeting: a portfolio management technique, decompose an aggregate measure of risk into its factor components to identify and manage contributions to portfolio risk.

risk management: the process of identifying, characterizing and reacting to risk to deal with potential losses.

scenario planning: a soft multicriteria decision-making tool, collaborative thought exercises to describe the workings of a system and evaluate the performance of choices.

spot market: the cash sales market, vs. the futures market.

value-at-risk: a portfolio management technique, construct probabilistic distributions of maximum expected loss for a given portfolio over a defined scenario.

vertical integration: internalization of different production stages into one firm.