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Real options for precautionary fisheries management

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Abstract

The 1996 Food and Agriculture Organization's (FAO) 'Guidelines on the Precautionary Approach to Fisheries and Species Introduction' raise important issues for fisheries managers, but fail to prescribe an approach for risk management. The distinguishing characteristics of the 'precautionary approach' are the inclusion of uncertainty and 'an elaboration on the burden of proof'. The FAO precautionary approach emphasizes that managers should be risk-averse, but does not provide tools for determining the appropriate degree of risk aversion. Consequently, application of the precautionary approach often leads to decision-making based on *ad hoc* safety margins. These safety margins are seldom chosen with explicit consideration of trade-offs. If the emphasis was shifted to choosing between competing uncertainties, then managers could manage risk. By attempting to avoid risk, managers may gain exposure to other risks and perhaps miss valuable opportunities. We place fishery management problems within the rubric of 'real investment' problems, and compare and contrast the consideration of risk by alternative investment frameworks. We show that traditional investment frameworks are inappropriate for fishery management, and furthermore, that traditional precautionary approaches are arbitrary and without basis in decision theory. Quantitative decision-making techniques, such as formal decision analysis (FDA), enable integration of competing hypotheses that help alleviate burden-of-proof issues. These techniques help analysts consider sources of uncertainty. FDA, however, can still be subject to arbitrary safety margins because such analyses often focus on determining which strategies best achieve, or avoid, targets that have been established without complete consideration of trade-offs. A managerial finance approach, real options analysis (ROA), is an alternative and complementary decision-making technique that enables managers to compute precautionary adjustments that couple the size of the 'safety margin' with the amount of uncertainty, thereby optimizing risk exposure and avoiding the need for arbitrary safety margins. We illustrate the advantages of an approach that combines FDA and ROA, using a heuristic example about a decision to re-introduce Atlantic salmon (*Salmo salar* L.) into Lake Ontario. Finally, we provide guidance on applying ROA to other fishery problems. The precautionary approach requires that managers consider risk, but considering risk is not the same as managing it. Here ROA is useful.

Keywords Decision analysis, investment, precautionary approach, real options analysis, risk

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Introduction

The 1996 Food and Agriculture Organization Guidelines on the Precautionary Approach to Fisheries and Species Introduction (FAO 1995) adapt the 'precautionary principle' (UNCED 1993) for fisheries management. Peterman (2004a) differentiates the precautionary principle from the precautionary approach, considering the latter to be a more flexible version of the former. The FAO guidelines outline a number of steps towards sound management such as to establish clear objectives, and emphasize the inclusion of uncertainty and an 'elaboration on the burden of proof', which would include 'the responsibility for providing the relevant evidence and the criteria to be used to judge that evidence' (FAO 1995). The importance of addressing uncertainty in fisheries management, however, was recognized well before these guidelines were published (e.g. Walters 1986). To date, precautionary approaches to fishery management have generally treated risk as an exogenous phenomenon and have largely focused on *ad hoc* biological limits to guide management decisions (Hilborn *et al.* 2001).

Alternative approaches for considering and managing risk continue to emerge in related fields. These may be considered alternative ways of implementing a precautionary approach, but were not explicitly prescribed by the FAO (1995). For example, a recent advance in managing risk in capital investments, real options analysis (ROA), can be employed as an objective and quantitative approach to manage a number of fishery-related risks. ROA allows 'precautionary adjustments' to be made based on the risk characteristics and uncertainties in a system by accounting for the 'option value'. Option value can be thought of as the value of flexibility; in other words, being able to make a better decision with more information in the future. This is associated with the ability to delay an irreversible decision and allow for uncertainty to be reduced.

Uncertainty about ecological and economic systems affects the outcomes that society experiences and creates risk. In this paper we take 'uncertainty' to denote a lack of information, while 'risk' describes the value and distribution of potential outcomes experienced by the society. Furthermore, perceptions of risk affect decision-making; outcomes are therefore conditional both on uncertainty and on managerial decisions (Shogren and Crocker 1999). Ergo, it is imperative that risk assessment and risk management be implemented jointly (Maguire 2004), because decisions affect both the likelihood and the consequences of events.

The precautionary principle states that any risk is 'too much', whereas the precautionary approach simply requires 'risk-averse' objectives (FAO 1995; Gerrodette *et al.* 2002; Peterman 2004a). In the latter case, this prompts the questions, 'what is an adequate level of risk aversion?' and 'how much risk is too much?' The precautionary approach prescription for risk aversion calls for the use of safety margins (FAO 1995; Gerrodette *et al.* 2002; Weeks and Berkeley 2000) and minimal safe standards (Prato 2005), such as biological reference points and limit points that are based on biological parameters (FAO 1995 – points 31, 62, 73i and 73j; Hilborn *et al.* 2001), to guide management decisions. Such safety margins are *ad hoc* adjustments to the precautionary principle, and often assume an inverse linear relationship between uncertainty and the appropriate size of the safety margin (Gerrodette *et al.* 2000). Moreover, such safety margins focus only on 'risks to fish stocks' without considering risk to society (Hilborn *et al.* 2001).

The precautionary principle and approach as described by the FAO (1995) do not help managers make risk exposure decisions when there are chances of adverse consequences associated with both enacting and forgoing a proposed programme (Farrow 2004). Indeed, forgoing a programme that carries risk also means forgoing the associated potential benefits or even windfalls. Moreover, the precautionary principle fails to value the opportunity to reduce uncertainty by acquiring information. When *ad hoc* safety margins are used as an approach to precaution, no value can be assigned to new information because such safety margins are not derived from a quantitative attribute of the uncertainty. The precautionary principle ignores benefits associated with accepting some degree of risk, and applications of the precautionary approach often downplay these benefits. Given these shortcomings, Peterson (2006) argues that the precautionary principle, and by extension the precautionary approach based on *ad hoc* safety margins, cannot be considered a true decision rule, although they may be valuable as an 'epistemic principle'.

An alternative approach to considering uncertainty, developed independently from the FAO precautionary approach, is the use of quantitative decision rules (Raiffa 1968; Morgan and Henrion 1990). The use of such approaches may be seen as alternatives to implementing a precautionary approach that explicitly considers uncertainty. These approaches work from the premise that the mere existence of benefits from a potential action does not justify the action, while the mere existence of costs or risk should not prevent the action.

Quantitative decision rules can be thought of as investment frameworks. Some investment frameworks can be used to balance the costs of risk with the costs of forgone opportunities in a way that captures the spirit of a precautionary approach without resorting to *ad hoc* adjustments (Morel *et al.* 2003; Farrow 2004). Many fishery managers are familiar with formal decision analysis (FDA) (Raiffa 1968; Peterman and Anderson 1999; Peterman 2004b) as an example of a quantitative decision rule approach. FDA can help managers determine which strategies best achieve objectives, while accounting for uncertainty. FDA, however, does not explicitly help to determine the degree of risk aversion that is merited, and therefore requires that the degree of risk aversion be defined as part of the objectives.

Determining the degree of risk aversion needed, or how much risk to accept, has been a significant hurdle in developing a generalized framework for fisheries management. In this paper we suggest that real options analysis (ROA) can be used in concert with FDA to help managers optimally balance benefits, costs and risks for fishery management decisions that are irreversible, but that can be delayed. We illustrate ROA using a stylized example of a decision to re-introduce Atlantic salmon into Lake Ontario and contrast the ROA approach with four alternative approaches: (i) standard expected net present value analysis, (ii) the precautionary principle, (iii) a minimum safe standard interpretation of the precautionary approach and (iv) a FDA-based stochastic expected net present value analysis. Using this example, we also demonstrate how ROA is conducted. This example illustrates a common class of fishery management problems, fish translocations, where risk is often not adequately considered (Jones and Dettmers in press).

Example: Atlantic salmon re-introduction

Atlantic salmon are native to Lake Ontario, but had been extirpated by 1896 due primarily to overfishing and habitat loss (Scott *et al.* 2005). Since 1880 fishery managers have unsuccessfully attempted to re-establish self-sustaining populations of Atlantic salmon (Scott *et al.* 2005). More recently, managers have successfully introduced non-native salmons and trout (*Oncorhynchus* and *Salmo* spp.) to the lake. Supported by intensive stocking programmes, these introductions have provided fishing opportunities and help control invasive alewives (*Alosa pseudoharengus,* Wilson). Managers are optimistic that re-establishment of self-sustaining populations of Atlantic salmon in Lake Ontario is now possible, because it is believed that exploitation can be managed and that habitat conditions are much improved, as evidenced by spawning non-native salmonines in Lake Ontario tributaries (Scott *et al.* 2003).

The re-introduction of Atlantic salmon comes at a cost, however. There are trade-offs to consider, including the loss of fishing opportunities for other salmonines, and the risk of Atlantic salmon re-introduction failure. The investment in Atlantic salmon re-introduction is irreversible. If re-introduction succeeds, then the ecosystem is altered; if it fails, then there are still costs associated with attempting re-introduction that are not fully recovered, such as forgone non-native salmon fishing opportunities. Moreover, there is uncertainty as to whether a re-introduction programme will be successful. There are multiple sources of uncertainty, including, but not limited to, how interactions with non-native species will affect recovery (Brown *et al.* 2005; Scott *et al.* 2005), the existence value of Atlantic salmon (Stevens *et al.* 1991), the future state of the fishery, the Atlantic salmon stock–recruitment relationship and others. A critical uncertainty is the interaction of Atlantic salmon with non-native prey, for which there is some evidence that consumption of non-native prey such as alewife, by Atlantic salmon leads to poor or failed reproduction (Brown *et al.* 2005).

In this paper, we use a decision about Atlantic salmon re-introduction to illustrate the advantages of the ROA approach to decision-making under uncertainty. For our example we focus on three critical uncertainties: the proportion of the prey base that is thiaminase-rich (i.e. alewives) (Brown *et al.* 2005), the effect of thiaminase-rich prey on reproductive success due to diet-induced thiamine deficiencies (Brown *et al.* 2005; Honeyfield *et al.* 2005) and the existence value for Ontario residents of Atlantic salmon in Lake Ontario. These three sources of uncertainty may be able to be reduced if the programme is delayed. For example, fisheries biologists would have the opportunity to better quantify trends in the prey fish community and the probability that alternative, thiaminaseless prey will increase in abundance in the future. Additionally, independent research programmes, which are not explicitly modelled, may provide better information on the role of thiaminase-rich prey in reproduction and on the existence and angling values provided by the salmonine community. These uncertainties may be reduced, but not be eliminated. Other sources of uncertainty such as the Atlantic salmon stock–recruitment relationship will persist.

We assume that policy-makers are only concerned with Ontario households and Lake Ontario anglers, and that the management goal is to maximize the discounted expected net benefits to these two groups in terms of net angling benefits and Atlantic salmon existence value, weighted equally. The actual process of arriving at objective functions is not covered. Furthermore, we assume that policy-makers are choosing whether or not to implement a single defined re-introduction programme.

We developed a simple, but plausible, model of the system (see Appendix). Our example is sufficiently detailed to simulate a management situation but is not intended to be prescriptive. We believe that the model structure is realistic, and thus is suitable for illustrating ROA, but our parameter assumptions are *ad hoc*, and we have not consulted with biologists or economists with expertise on Lake Ontario salmonine fisheries. Thus, our conclusions should not be interpreted as management recommendations for the Lake Ontario fish community.

Investing in Fisheries

To contrast different approaches to making decisions in an uncertain world, it is helpful to think of the management of a fishery as an investment problem. Investments involve incurring costs in order to achieve future benefits, so stocking, or reducing harvests to affect future harvests, are examples of fishery investments. An investment should be made if it maximizes the discounted net benefits. However, just as with any other investment, fishery investments are not risk-free. For a given investment decision, there is always a range of possible outcomes, some more likely than others, and some more favourable for the investor than others. In our example, the 'investor' would be a management group, managing the Lake Ontario salmonine community in trust for society. The investment is hatchery production costs and forgone non-native salmonine fishing benefits, while the anticipated return is the existence and angling values from restored Atlantic salmon.

Investment frameworks help investors make decisions. Some investment frameworks help determine how much risk is acceptable given an objective and the current level of understanding about the underlying asset, i.e. the fishery. Other, less sophisticated approaches require decisions about risk to be made *a priori*. Managers already regularly consider, perhaps qualitatively, the benefits, costs and risks when evaluating programmes. Indeed, precautionary approaches are founded on the idea of avoiding unanticipated and costly outcomes (Weeks and Berkeley 2000; Gerrodette *et al.* 2002). Hilborn *et al.* (2001) and Edwards *et al.* (2004) call for thinking of fishery management in an investment framework, and for the development of an investment framework that can help managers allocate risk over a portfolio of uncertain events.

When managers adopt an investment approach, it is vital that they have a clear understanding of the concepts of 'costs' and 'benefits.' Investors aim to maximize *net* benefits, and think of costs as the forgone opportunities or opportunity cost associated with a decision. In other words, the net benefits from the next best alternative are the forgone opportunities associated with a given decision. Therefore, the net benefits from the Atlantic salmon re-introduction are the additional net benefits earned under re-introduction relative to the net benefits that could have been earned by allocating prey and managerial resources to the non-native salmonine fishery.

Traditional non-precautionary and precautionary analyses: approaches and limitations

Benefit–cost analyses commonly, albeit informally, are conducted to inform fishery management decisions. For example, sea lamprey (*Petromyzon marinus* L.) control in the Laurentian Great Lakes has been justified on the basis of benefit–cost analysis (Stewart *et al.* 2003). The simplest decision-making rule states that decision-makers should prefer a project when the expected benefits outweigh the expected costs, i.e. when the net benefits from the *decision* are positive.

$$\text{Proceed with the programme if:} \quad E[\mathit{Benefits} - \mathit{Costs}] \geq 0. \tag{1}$$

Here, benefits are the expected net gains from advancing a project, and costs are the expected net gains with the alternative project. Costs are defined in the previous section.

The decision rule formalized by Equation (1) is known as the 'net present value (NPV) rule' for capital investment, as expected future benefits and costs are first converted to present value through a discounting process, and then the programme proceeds if the net value is positive. Discounting accounts for time preferences, by which people desire to have the benefits today and pay the costs tomorrow (Conrad 1999). The NPV rule, illustrated in Fig. 1 (line A) with a decision plot, is an appropriate decision-making framework for choosing among a discrete set of projects or opportunities provided there is no uncertainty, it is not possible to delay the decision, or the decision is completely reversible.

The NPV rule maximizes net benefits when choosing between two projects and the choice is reversible; i.e. there are no fixed or sunk costs (Dixit and Pindyck 1994). Uncertainty however, introduces a type of fixed or sunk cost. In the presence of uncertainty there is value, known as the option value, in the opportunity to delay the decision until uncertainty is reduced (Dixit and Pindyck 1994). Option value is also known as quasi-option value (Fisher 2000). When making an irreversible investment decision this option value is 'paid' as a fixed cost. Accordingly, the NPV is often inappropriate for fishery management and surely inconsistent with a precautionary approach that explicitly considers

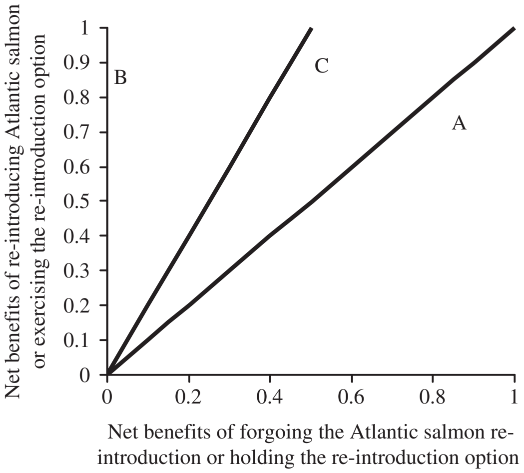

Figure 1 A decision plot illustrating how a decision to enact a programme would be evaluated under different decision rules. When the best estimate of the relative benefits falls below and to the right of the decision boundary, the programme is prohibited. For a given rule, the programme is enacted only when the best estimate of the relative benefits fall above and to the left of the decision boundary. Line A represents the case of the net present value rule, and the slope of the line equals 1. Line B represents the precautionary principle, and the slope of the line equals infinity. Line C represents a precautionary approach and the slope is greater than one, but less than infinity. In the real options analysis case, the slope of line C is chosen to optimally balance benefits and costs while accounting for risk.

uncertainty. Indeed, many fisheries management decisions are to some degree irreversible, as illustrated by the re-introduction of Atlantic salmon, and often there is an opportunity to delay, thereby preserving the option value.

Attempts have been made to modify the NPV rule to account for risk by increasing the discount rate. The rationale for this approach is that as the project risk increases, so should the required rate of return (Hull 2003, p. 660). In business applications it is possible to estimate the 'price of risk' by observing the rate of return earned by similarly risky projects. However, natural resource management decisions are often unique so that any such comparison is problematic, and rates of return may be unclear. There is no generally accepted practice to price risk for public projects and indeed risk often remains unpriced when public projects are evaluated (Lesser and Zerbe 1994; Van Ewijk and Tang 2003). The FAO (1995) recommends that 'appropriate' discount rates be used but provides little guidance in determining such rates. Moreover, a risk-adjusted discount rate cannot be calculated accurately when calculated independently of the optimal decision, as management decisions and management flexibility alter risk characteristics (Copeland and Antikarov 2003; Brandao *et al.* 2005).

When the future is uncertain, or delayable decisions are irreversible, a 'precautionary approach' is more appropriate (Conrad 1999). Rather than using a risk-adjusted discount rate to account for risk, a precautionary adjustment (*PA*) or 'hurdle' is applied between the benefits and costs (Dixit and Pindyck 1994), making the decision rule shown next.

$$\text{Proceed with the programme if:} \quad E[Benefits - Costs] \geq PA > 0. \tag{2}$$

The *PA* is the option value. Therefore, if and only if, the size of the *PA* is chosen optimally then Equation (2) maximizes discounted expected net benefits when choosing between two projects. Equation (2) can be rearranged so that the *PA* is more easily recognized as a cost.

$$\text{Proceed with the programme if:} \quad E[Benefits - (Costs + PA)] \geq 0. \tag{3}$$

The notion of a *PA* is implicit in the precautionary principle and precautionary approach. In the case of the precautionary principle, the *PA* is set at infinity (Fig. 1, line B), and there is no decision to make. The minimum safe standard precautionary approach is less extreme, and the *PA* is chosen so that $0 < PA < \infty$, often in an *ad hoc* fashion (Fig. 1, line C). It is important to point out that in the minimum safe standard approach the *PA* may not be explicitly chosen, but rather is implicitly chosen by imposing constraints. For example, reference and limit points are a common way of implementing the precautionary approach for exploited fisheries (Hilborn *et al.* 2001), but usually do not take explicit account of trade-offs. They are generally *ad hoc* adjustments to some biologically defined parameter (Quinn and Deriso 1999). Indeed, determining the value of a specific reference point is a scientific question, but which reference point or limit to choose is a socio-political decision that involves making trade-offs (Hilborn *et al.* 2001). The problem with this approach is that the magnitude of the *PA* is not coupled to the level of risk. Because the *PA* in this approach is not coupled to the level of risk, this approach can lead to a *PA* that is too small or too large, potentially resulting in inadequate precaution or forgone beneficial management actions. Peterson (2006) argues that given the arbitrary nature of these approaches, they are inconsistent with rational decision theory. If the *PA* were chosen in a way to optimally balance benefits, costs and risks, then the approach would be consistent with rational decision theory.

Simulation approaches to quantitative decision that incorporate uncertainty

The need to explicitly include uncertainty in decision-making has led to approaches based on stochastic, Monte Carlo simulations. These techniques involve developing mathematical models that represent different hypotheses about system behaviour that can be implemented on a computer. These models include random error terms to simulate stochastic events and the degree of managers' uncertainty about parameters or processes. Using techniques to integrate alternative models (Punt and Hilborn 1997; Burnham and Anderson 2004) allows one to address process uncertainty. Formal inclusion of alternative hypotheses defuses conflict by avoiding the need to choose *a priori* among competing hypotheses. This approach has been advocated by some as fundamental to implementing a precautionary approach in fisheries (Punt 2006).

FDA is an increasingly popular way to analyse the outputs of these stochastic simulation models. Punt (2006) reviews the application of this approach in precautionary fishery management. Peterman and Anderson (1999) describe an eight-step approach to FDA (Table 1), although not all steps are necessary for all decision analyses. To compare a decision with its alternatives, combinations of outcomes are valued using the NPV rule, with the analyst working backwards in recursive fashion on a decision tree (Peterman and Anderson 1999). This approach works well for simple problems. Stochastic dynamic programming (Conrad and Clark 1987; Bloczynski *et al.* 2000) works in a similar fashion and may be used to efficiently find optimal solutions for moderately complex decision trees. However, as a result of computational limitations, both approaches become infeasible when there are multiple sources of uncertainty with multiple decision nodes.

This makes accounting for the opportunity to delay a project difficult in FDA. Therefore, the opportunity to delay is often not explicitly considered, and the option value is not computed. Thus, FDA typically results in a decision to proceed or cancel a project, which would mean to re-introduce Atlantic salmon or not in our worked example. Following this approach the option to delay is not considered formally. The FDA approach provides a useful way of identifying decision possibilities and sources of uncertainty. By characterizing sources of uncertainty, one can prioritize future research. FDA can also be taken a step further, and the expected value of information can be computed. The value of the information can be used to determine how many resources should be invested in research (Ades *et al.* 2004), but the value of the information generally does not account for the time delay and the intertemporal cost of collecting information.

FDA helps managers consider uncertainty in the spirit of a precautionary approach. FDA, however, is not helpful in determining the size of a *PA*, or locating a decision boundary for complex problems. Therefore, a risk-management tool is needed to link the size of the *PA* with the uncertainties in the system.

Real options analysis

ROA was developed to analyse uncertain investment decisions: (i) when the decision is irreversible, and (ii) where there is the opportunity to delay making the investment until more information is gained (Dixit and Pindyck 1994). ROA need not be highly precise, as the objective of ROA is to inform broad decision-making under uncertainty and irreversibility (De Neufville 2003). ROA provides a quantitative framework where the *PA*, the option value, is determined as a function of the risk associated with the decision (Farrow 2004). ROA accounts for the added value of being flexible and waiting for some uncertainty to be resolved. This is a key distinction between ROA and FDA. Whereas the latter can be supplemented by value of information computations, ROA makes this ingredient of decision-making explicit and internal. ROA imputes a cost when the opportunity set contracts and a benefit when it expands. As an extension to the precautionary approach, ROA provides a non-arbitrary means to calculate the size of the *PA* that is coupled with the degree of uncertainty.

An option can be defined as the right, but not the obligation, to take an action. ROA has managers to

Table 1 Steps to conducting a formal decision analysis (FDA; *sensu* Peterman and Anderson 1999) and real options analysis (ROA).

FDA	ROA
1. Clearly state the management objectives and indicators	1. Define and clearly state the objective and constraints
2. Clearly state the management possibilities	2. Clearly define the option
3. State uncertainties about the state of nature	3. Describe the system and the uncertainty in the system
4. Assign probabilities to the uncertain states of nature	4. Assign probabilities to the uncertain states of nature
5. Develop models to calculate the outcomes associated with each management option	5. Simulate the dynamics of the uncertainty and the decision to hold/exercise the option
6. Develop a decision tree	6. Use the model to estimate the drift and volatility of outcomes
7. Rank management options	7. Calculate a precautionary multiplier to evaluate the decision
8. Conduct sensitivity analysis	8. Conduct sensitivity analysis

rephrase the question from, 'Should we take action *X*?' to, 'When should we exercise the option that we hold to initiate action *X*?' An appealing aspect of using ROA is that the manager no longer delays the decision for more information, which implicitly makes a decision. Instead the manager decides either to go ahead with a programme or to wait for more information, and this explicitly makes a decision, thereby delaying the programme's start. The difference is subtle, but in the latter situation the manager is explicit about the decision being made.

As relative uncertainty increases so does the value of the option (Copeland and Antikarov 2003, p. 87). As uncertainty is reduced, managers may learn that the programme provides adequate net benefits and therefore should proceed. Conversely, they may learn that the programme does not provide adequate net benefits. In this case the value of the option becomes zero. The manager may make a final decision as the option to make a 'bad' decision is trivial. Options are important in the case where (i) expected net benefits from the project are positive, and where (ii) the relative risk associated with exercising the option is greater than that of holding the option. Some systems may be highly uncertain regardless of the decision to hold or exercise the option, in which case this risk is not associated with the decision.

In ROA, the *PA* can be derived in the form of a precautionary multiplier, Γ that is based on the characteristics of the system in which the option exists (Farrow 2004).

$$PA = Costs \times (\Gamma - 1), or\, \Gamma = 1 + PA/Costs. \quad (4)$$

The use of a precautionary multiplier, as opposed to a *PA*, is mathematically convenient. Equation (4) shows that Γ may be expressed as function of the *PA* and vice versa.

The simplest way to characterize a programme resulting from a decision is by the best estimate of discounted expected net benefits resulting from that decision, B_i, where i indexes the decision. The precautionary multiplier accounts for the additional risk of exercising the option ($i = X$), relative to holding the option ($i = H$). When programme *X* carries no additional risk, i.e. $\Gamma = 1$, it should proceed provided $B_X - B_H \geq 0$ or $B_X/B_H \geq \Gamma = 1$ (B_X = benefits and B_H = costs). When programme *X* is relatively risky, the requirement to proceed becomes $B_X / B_H \geq \Gamma > 1$. In a graphical representation, the optimal slope of the decision boundary (Fig. 1, line C) is equal to Γ. In most cases, the net benefits gained using the ROA minus the net benefits gained using the NPV approach is equivalent to the expected value of information (Fisher 2000).

Conducting ROA

We now use the Atlantic salmon example to demonstrate how ROA can be conducted and contrast the results with other approaches. We recommend eight steps to implement ROA in fisheries that parallel Peterman and Anderson's (1999) eight steps to FDA.

The first step is to carefully formulate a single objective that can be maximized or minimized; this objective can be subject to many constraints. A common objective is to maximize the discounted expected net benefits associated with a fishery or aquatic ecosystem to a defined group of stakeholders. The difficulty faced in this step comes in deciding how to weigh the net benefits gained by different stakeholders, as net benefits are never distributed equally. It is well known that the formation of an objective cannot be based on objective analysis, but requires value judgements (Arrow 1950). In the Atlantic salmon example the manager's objective is assumed to be to maximize the sum of discounted expected net benefits from angling and from the existence value of Atlantic salmon, weighted equally over a time span of the next 50 years. The constraints are imposed by way of the system model that includes Atlantic salmon and non-native salmonines, high- and low- thiaminase prey, anglers and Ontario households. In reality, arriving at suitably weighted objectives is very difficult. An alternate approach would be to allow the formulation of alternately weighted objectives, and then examine how robust the decision to exercise the option is to the alternative weightings.

Defining the option, step 2, requires that managers correctly identify the option held. The way the objective is defined, and specifically how net benefits are weighted, can influence the formation of the option (Farrow 2004). The option is to make an irreversible decision. Using the phrase 'the right, but not the obligation to …' can help. In our example, we specify that managers have the right but not the obligation to commit to a 25-year Atlantic salmon stocking re-introduction programme. This assumes that the start date of the programme could be delayed. From an operational perspective, ROA is appropriate when the $B_X > B_H$, and B_X is relatively risky, creating the possibility that holding the option would be preferred. Not all situations will conform to these two criteria. In this paper we are considering options that do not expire. In some cases, however, options do expire. For example, exploited fishery managers only have the right, but not the obligation, to set a fishing mortality rate for 2009 up to the beginning of that year. Then they are obligated, and the decision cannot be delayed.

Steps 3 and 4 involve developing a model of the system. Multiple models, which implement competing hypotheses are used to describe the current understanding of the processes that take place in the system. Parameters are estimated from the available data using these models. By explicitly developing models, the analyst clearly states the current understanding of the system and the sources of uncertainty. It is possible that the same system model may be used in ROA as in FDA. Figure 2 represents the conceptual model used in our example analysis; model details and uncertainties are described in the Appendix.

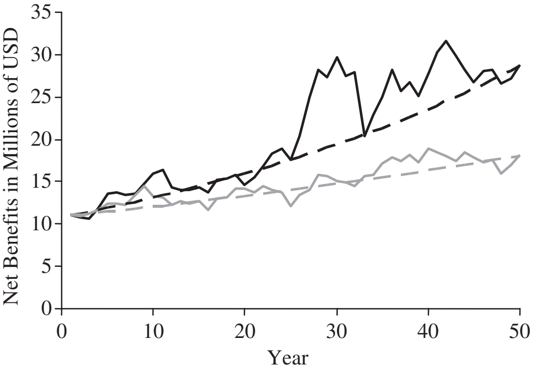

Figure 3 Predictions of future benefits and dynamics of uncertainty, resulting simulations of exercising (black line) and holding (grey line) the option to re-introduce Atlantic salmon. Exercising the option has higher drift (0.02) and volatility (0.09). Holding the option has lower drift (0.01) and volatility (0.06). The dotted lines represent the drift associated with the two decisions respectively. For this simulation the volatility correlation is 0.4.

The next step, step 5, is to simulate the dynamics of the uncertainty. Stochastic simulation procedures project the net benefits of the decision to exercise the option and net benefits of the decision to hold the option. Model data are generated by running a pair of simulations, one where the option is exercised and one where the option is held. The solid lines in Fig. 3 represent one such pair of stochastic simulations from the Atlantic salmon example. Pairing the simulations is important for the comparison of relative risk. In FDA, the distribution of potential future states of the world is of primary interest. A subtle difference in ROA is that we are additionally interested in understanding the dynamics implied by the uncertainty.

In step 6, the model data are used to characterize the dynamics of the uncertainty. This includes calculating the drift or volatility, and the volatility covariance or correlation. Campbell *et al.* (1997, p. 362) derived formulae that could be applied to simulation data and that calculate drift and volatility by maximum likelihood. The approach by Campbell *et al.* (1997) assumes that net benefits

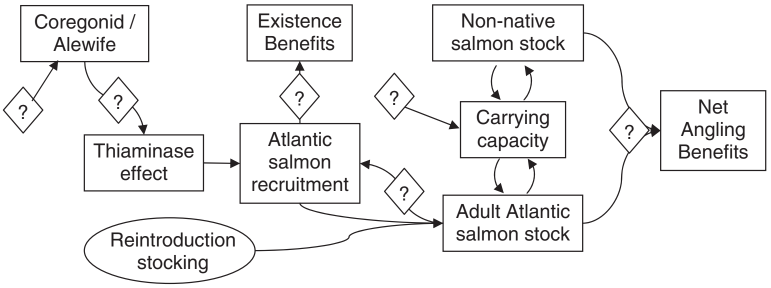

Figure 2 A conceptual model of the Atlantic salmon re-introduction system. Boxes represent state variables, the oval represents the potential policy action, and the diamonds with a '?' represent sources of uncertainty that have been incorporated into the model as stochastic processes. Some uncertainties affect the dynamics with a state variable box and are connected to the box by an arrow (e.g., salmon carrying capacity); other uncertainties affect processes that connect boxes and are incorporated into the arrows that link state variables (e.g., thiamine deficiency effects on Atlantic salmon recruitment).

follow geometric Brownian motion (GBM). Copeland and Antikarov (2003) and Morel *et al.* (2003) point out that estimation based on the GBM assumption is appropriate for combining multiple sources of uncertainty into a single multiplicative process, even if some sources of uncertainty are correlated or mean reverting. Drift and volatility are estimated from the change in log net benefits over time. Drift is the mean of the change in log net benefits. Drift can be thought of as the expected per cent of growth in net benefits over time, capturing the general direction and magnitude of change in net benefits over time (the dashed lines in Fig. 3). Volatility is the standard deviation of log change in net benefits over time. In Fig. 3, the decision to exercise the option (black) has a larger drift and higher volatility than the decision to hold the option (grey). A discount rate is also needed for calculation of the precautionary multiplier. This discount rate only accounts for time preference and does not include a risk premium.

Step 7 calculates the precautionary multiplier. The precautionary multiplier for a single option that does not expire is calculated by solving for a function to maximize the expected discounted difference between the net benefits associated with exercising and holding the option (Morel *et al.* 2003). The mathematical details of solving for Γ, with a GBM and alternate assumptions, are addressed by Dixit and Pindyck (1994) and Morel *et al.* (2003). These authors present a formula that maximizes the expected net benefits that depends only on: (i) the drift and volatility estimates of paired simulations of holding and exercising the option, (ii) the correlation between the change in log net benefits of exercising and holding the option and (iii) the discount rate. The optimal precautionary multiplier, Γ, satisfies:

$$r = \alpha_H + \frac{\Gamma(\alpha_X - \alpha_H)}{\Gamma - 1} - \frac{\Gamma\Sigma}{2(\Gamma - 1)^2}, \quad \text{where } \Sigma = -\sigma_X^2 + 2\zeta\sigma_X\sigma_H - \sigma_H^2 \tag{5}$$

where r is a discount rate that accounts for time preference and is chosen *a priori*, α_i and σ_i are drift and volatility parameters, respectively and are estimated from a pair of simulations and ζ is the correlation coefficient also estimated from the simulation data. A large correlation coefficient implies less uncertainty over the optimal benefit–cost ratio (Dixit and Pindyck 1994). A negative correlation coefficient amplifies the affect of uncertainty; in effect, given uncertainty in the drift and volatility parameters, a reversal in which policy is more beneficial is more likely (Kassar and Lasserre 2004).

Equation (5) facilitates an intuitive appreciation for ROA and can be thought of as an investment rule that serves as the optimality condition for Γ. The left-hand side of the condition in Equation (5) is the discount rate. The discount rate is equal to the opportunity cost of the decision, interpreted as the expected return on an alternative investment. As a whole, the right-hand side (RHS) of condition (5) is the rate of return that can be expected from optimal risk management in the fishery. These terms should be equal; otherwise it would be optimal to accept more or less risk to match returns that could be earned elsewhere. The first two terms on the RHS of condition (5) are a weighted sum of the drift coefficients of holding and exercising the option. This sum is interpreted as the expected returns from the fishery. The first RHS term is the drift parameter or rate of return from holding the option. The second RHS term is the expected net gain from exercising the option weighted by the precautionary multiplier, which accounts for the control that managers have over risk exposure. The third RHS term is sometimes called the total cost of the relative risk (Hull 2003). A precautionary multiplier that makes society indifferent between the expected gains of holding the option and exercising the option is identified by solving for Γ to satisfy equation (5).

The final step, 8, would be to conduct sensitivity analysis. This could include sensitivity of the preferred decision to alternate weightings of the objective function.

ROA enables the analyst to account for uncertainty and risk with only a single pair of simulations. However, we can better account for uncertainty and risk by running many simulations. This helps us account for the uncertainty in the precautionary multiplier and costs little. We conducted 1000 simulations of the Atlantic salmon decision model and calculated Γ for each. We then contrasted decisions based on ROA with those made based on other approaches.

Results: comparing ROA with other approaches

Neither the NPV rule nor the precautionary principle accounts for risk. The NPV rule approach does not account for uncertainty. All standard deviations for model parameters are zero and only the 'best' model for each process is used. For our example, assuming a discount rate of 6.5%, the benefit–cost ratio would be 1.83. This implies that if there were no uncertainty, then it would be preferable to initiate the Atlantic salmon re-introduction programme. Conversely, the precautionary principle would imply that re-introduction should not begin because there is indeed uncertainty about the result.

The precautionary approach, FDA and ROA all consider uncertainty. The results from 1000 simulations presented in Table 2 can be used to analyse a minimum safe standard precautionary approach, a precautionary approach using an FDA-based stochastic expected NPV analysis, and ROA. We placed no constraints on the type of outcome from any given pair of simulations, and this allowed for five types of outcomes. The first division is where $B_X/B_H > 1$. If $B_X/B_H > 1$ and $\sigma_X < \sigma_H$, then proceeding with the programme provides net benefits and is relatively less risky. Such a pair of simulation outcomes provides support for proceeding with the programme; no further calculations are necessary. If, on the other hand, $\sigma_X > \sigma_H$, calculation of a precautionary multiplier, Γ, is merited (following Morel *et al.* 2003). In this case, if $B_X/B_H > \Gamma$, then the simulation outcomes provide support for proceeding. If, however, $B_X/B_H < \Gamma$, then the simulation outcomes provide support for delaying the start of the programme to reduce uncertainty.

The other two cases relate to the situation where simulation results indicate $B_X/B_H < 1$. It is straightforward if $\sigma_X > \sigma_H$. Then, benefits are not expected to exceed the costs and the Atlantic salmon re-introduction is relatively risky. Thus, the programme should not proceed, and such simulations provide support for 'scrapping' the option. The final case is where simulation results yield $\sigma_X < \sigma_H$. In this case, not stocking Atlantic salmon is relatively risky and can be interpreted as support for holding the option and continuing to consider the re-introduction.

First, consider a stochastic expected NPV analysis based on FDA. Assuming a discount rate of 6.5%, the benefits exceed the costs in 94% of the simulations (Table 2). This result is stable across discount rates. The fact that in more than 50% of the simulations Atlantic salmon stocking provides positive benefits would be interpreted as support for the programme. Indeed, the proportion of times that Atlantic salmon stocking provides positive net benefits is so much greater than 50% that it can be interpreted as strong support.

Brandao and Dyer (2005) emphasize that when applied equivalently FDA and ROA give the same result. However, most FDA-based stochastic expected NPV analyses differ from ROA in that they do not account for the opportunity of delaying the decision. An FDA approach to this problem could incorporate a sequence of choices to stock (exercise) or not stock (hold) in successive years, but the resulting decision tree would be very complex, leading to probable computational constraints. For example, consider six sources of uncertainty and assume that each uncertainty can be represented by two alternative hypotheses. In this case, the decision tree branches 64 times at each decision node, expanding exponentially as it does so. An approach that ignores the opportunity to delay would only be appropriate in the extreme case of 'now or never' decisions.

Now consider a minimum safe standard precautionary approach. We might say that net benefits

Table 2 Benefit–cost ratio for 1000 stochastic simulations of Atlantic salmon re-introduction, for three different discount rates. The simulations are further partitioned by volatility and compared with the calculated precautionary multiplier.

Discount rate			6.5%	4%	10%
$B_X/B_H > 1$	$\sigma_X < \sigma_H$	Proceed	0.00	0.00	0.00
	$\sigma_X > \sigma_H$	Exercise, $B_X/B_H > \Gamma$	0.63	0.18	0.70
	$\sigma_X > \sigma_H$	Hold, $B_X/B_H < \Gamma$	0.31	0.76	0.24
	Total		0.94	0.95	0.94
$B_X/B_H < 1$	$\sigma_X > \sigma_H$	Cancel	0.05	0.05	0.06
	$\sigma_X < \sigma_H$	Hold	0.01	0.01	0.01
	Total		0.06	0.05	0.06
Proportion of time ROA 'recommends' proceeding			0.63	0.18	0.70
Proportion of time ROA 'recommends' delaying to reduce uncertainty			0.32	0.77	0.24

ROA, real options analysis.

would have to exceed the costs by some arbitrary value. If this value were greater than zero, as is implied by the precautionary approach, the support for the stocking programme would weaken. How much it would weaken would be dependent of the choice of the value by which benefits would have to exceed costs.

The ROA approach resolves this problem. Stocking Atlantic salmon results in higher volatility for all simulations result in $B_X/B_H > 1$. This is not accounted for in the FDA-based stochastic expected NPV analysis. That is, by simulating the dynamics implied by the measures of uncertainty, it is recognized that stocking Atlantic salmon is relatively risky. But is the risk worth it? In 63% of the simulations where stocking Atlantic salmon provides net benefits, proceeding with re-introduction is expected to provide more net benefits than delaying the re-introduction, even accounting for this risk. In a small number of cases stocking Atlantic salmon is less risky, but these cases only occur when the net benefits of stocking Atlantic salmon do not exceed the net benefits from not stocking Atlantic salmon. Such cases imply that managers should continue considering, but not yet initiate, re-introduction.

When ROA is used, starting the Atlantic salmon stocking programme is supported for a 6.5% discount rate, but the support is weaker than from FDA. This is because using ROA takes into account the risk and the opportunity to reduce uncertainty. The discount rate matters (Table 2). A lower discount rate implies less support for the Atlantic salmon stocking programme. This counter-intuitive result occurs because managers are more patient, and willing to wait longer to reduce uncertainty. That is, the opportunity to reduce uncertainty or the future option value is valued more highly when the discount rate is small. Conversely, a high discount rate implies greater support for initiating the stocking programme now. In this case, managers place a lower value on the ability to reduce uncertainty, and therefore the results more closely align with the stochastic benefits cost analysis. The benefit cost ratio also increases with a decrease in the discount rate so that the future net benefits of the optimally managed programme are also weighted more heavily. The important question is does a decrease in the discount rate increase Γ or the benefit–cost ratio faster? This has to do with how uncertain the analyst is about the system.

Conclusion

Fisheries analysts continue to face the challenge of appropriately incorporating risk and uncertainty into management (Peterman 2004b). There is increasing interest in using portfolio theory and other approaches from business to manage risk in fisheries and conservation (Edwards *et al.* 2004; Koellner and Schmitz 2006). ROA is on the cutting edge in managerial finance and is used increasingly in strategic firm management (Copeland and Antikarov 2003). ROA has been proposed as a decision framework for forest planning (Yin 2001), wilderness preservation (Conrad 2000), invasive species management (Saphores and Shogren 2005) and air pollution reduction (Farrow 2004). In this paper, we have laid out an approach for operationalizing ROA in fisheries management and illustrated the advantages of combining ROA with decision analysis techniques. We recommend that fishery management lead the way in adopting ROA as a potential management tool.

The FAO (1995) guidelines emphasize the importance of considering uncertainty, but do not offer explicit guidance on how to optimally manage risk. Current precautionary approaches emphasize risk aversion, rather than choosing between competing uncertainties to manage risk. This can lead to *ad hoc* decision-making based on arbitrary safety margins. Quantitative decision-making techniques (e.g. FDA) allow analysts to explicitly *consider* uncertainty and provide a way to integrate competing hypotheses and ideas about the system and address some burden of proof issues. Moreover, these techniques enable analysts to identify sources of uncertainty, research priorities for reducing uncertainty and forecast future states of the world. FDA, however, can be plagued by the arbitrary nature of selecting performance measures.

ROA expands FDA-enabling managers and analysts to *manage* risk. ROA enables managers to compute precautionary adjustments in a way that couples the size of the 'safety margin' with the amount of uncertainty in the dynamics of the system, thus optimizing risk exposure. ROA imputes the costs of uncertainty and irreversibility. Furthermore, ROA also accounts for the importance of the trade-offs between the benefits of action and the costs of preserving or expanding an opportunity set, as well as between the benefits of learning and the costs of delaying decisions. Ultimately, the FAO (1995) precautionary approach can serve as a valuable epistemic principle, encouraging managers to perform analysis and to think more carefully about risk. Considering risk, however, is not the same as managing it. ROA is a powerful tool that enables managers to manage risk within an optimal risk exposure framework.

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Appendix: The Atlantic salmon re-introduction model

The model of Atlantic salmon re-introduction trade-offs was developed to illustrate the ROA approach; we have not attempted to incorporate the realism and details that would be necessary for a 'real-world' analysis of this policy issue, mainly because such details would require significant exposition and detract from the purpose of the illustration. A conceptual diagram of the model is illustrated in Fig. 2. This appendix provides further details about the model. Each state variable, represented by boxes in Fig. 2, is addressed in turn.

Salmonine predators in Lake Ontario feed primarily on exotic prey fish species (alewife and rainbow smelt *Osmerus mordax*) that are rich in thiaminase. Historically the main prey species in Lake Ontario were members of the genus *Coregonus,* which are low in thiaminase. Efforts are underway to increase the abundance of the historic prey fish community (Eshenroder and Krueger 2002). We have assumed that the future relative abundance of thiaminase-rich and poor prey is uncertain, leading to uncertainty about the proportion of thiaminase-rich prey in Atlantic salmon diets. In our model we used the simulated ratio of coregonids to alewife to represent the ratio of low-to-high thiaminase prey consumed by Atlantic salmon. The percentage of either type of prey item available is capped at 95%. It is assumed that alewife initially make up 95% of the available prey. To represent uncertainty in the future relative abundance of different prey types, we modelled the ratio of coregonids to alewife (c/a) as $(c/a)_{t+1} = z_t(c/a)_t + (c/a)_t$, where z_t is a normally distributed autoregressive process. This allows for both increases and decreases in the (c/a). Indeed, in some simulations, coregonids never exceed 5%.

There is an established link between low thiamine levels and juvenile mortality in salmonids, but the link between thiaminase-rich prey and mortality is still uncertain (Brown *et al.* 2005). Therefore, we include uncertainty in the process by which consumption of alewives exposes Atlantic salmon to thiaminase. We assume that exposure is proportional to the average annual ratio of alewife to coregonids in the Atlantic salmon diet. We also assume that age 0 Atlantic salmon do not consume prey fish and only 50% of the diet of age 1 Atlantic salmon is prey fish. This causes older and larger salmon to have higher average annual exposure to thiaminase-rich prey fish and is consistent with the empirical findings of Werner *et al.* (2006).

A portion of each age class of Atlantic salmon is assumed to spawn each year. A Ricker spawner–recruit relationship, $R = \alpha S e^{-\beta S}\epsilon$, is used where α and β are parameters, R is recruits from an age class of spawners S and ϵ is an autoregressive log-normally distributed error term. It is assumed that exposure to thiaminase-rich prey exponentially decreases the maximum reproductive rate per spawner α in the spawer–recruit relationship. The parameter α is replaced by $\alpha' = \alpha e^{-Ep}$, where E is the average annual ratio of alewife to coregonids in the diet of spawners of a particular age class and p is a truncated normally distributed error term that is constrained to the unit interval. This makes the realized stock-recruitment relationship for an age class of spawners $R = \alpha' S e^{-\beta S}\epsilon$.

The option is assumed to be a commitment to stock 500 000 age 1 Atlantic salmon for 25 years. Stocked fish are not considered part of recruitment. Atlantic salmon of all ages experience age-specific natural and fishing mortality. Stocked fish experience 50% stocking mortality. Fishing mortality is multiplied by selectivity at age (assumed to be equal to the proportion of fish in that age class that spawn) and applied as an age-specific fishing mortality rate. We assume a constant fishing effort so that fishing mortality is proportional to stock size (in numbers), but that the translation of fishing effort to fishing mortality is uncertain and is modelled as uncertainty in the catchablity coefficient. Finally, age-specific natural mortality is applied.

We assume that there is a biomass of salmonines that can be supported in Lake Ontario and is independent of the ratio of alewives to coregonids. We convert the numbers of Atlantic salmon to biomass using weight-at-age, subtract this from the total biomass and assume that non-native salmon comprise the remaining biomass. Non-native salmon dynamics are not explicitly modelled. Non-native salmon biomass is then converted to numbers. The actual carrying capacity for salmon varies year to year by an order of one autoregressive process.

Just as understanding ecological interactions in a fishery is complex, so is valuing the fishery. We have made a number of simplifying assumptions, as we did with the ecological portion of the model, to facilitate an illustration of ROA. For a more complete review of valuing recreational fisheries, see

Hoehn *et al.* (1996). We assume that the marginal value of catching a Pacific salmon is \$16.43USD (Johnston *et al.* 2006 adjusted to 2003 USD), but that the relative value of angling for Pacific and Atlantic salmon is unknown. We assume that the net angling value of Atlantic salmon is some fraction of the value of for Pacific salmon, but this fraction is uncertain and follows a log-normal distribution.

There is a large degree of uncertainty associated with existence values (Stevens *et al.* 1991), but these can count for a substantial portion of the value of fish stocks to society (Loomis and White 1996a;b). Total existence value is generally increasing in stock size (Loomis and White 1996a), but we expect the marginal existence value to decrease with increasing stock size. Moreover, total existence value is not dependent on the stock alone. Because existence values are non-rival, i.e. one person valuing the existence of Atlantic salmon does not preclude another from valuing Atlantic salmon, the number of people or households that value the species must be considered. Stevens *et al.* (1991) reports an average annual willingness to pay by Massachusetts households to prevent the extinction of Atlantic salmon of \$7.93USD. This is consistent with the willingness to pay for other species (Loomis and White 1996a). We adjust this value to 2003 US dollars and then multiple it by the approximate number of households in Ontario in 2003 to get the annual existence value of Atlantic salmon to the Province of Ontario. We assume that this existence value corresponds to stock of 200 000 age 2 wild-spawned fish; a measure that represents a stock likely to continue existing. We assume that the marginal existence value per fish declines exponentially with increases in wild recruited fish. The total existence value is $\int_0^N xae^{-bx}dx$ where N is the number of age 2 wild-spawned Atlantic salmon, a and b are parameters and x is a dummy of integration. We calibrate this functional form so that at 200 000 age 2 wild-spawned Atlantic salmon, the total existence value of Atlantic salmon is equal to that calculated for the Province of Ontario. We then model a as a random variable to account for uncertainty in the existence value.

Table of parameter values used in the Atlantic salmon re-introduction example

Age 1 Atlantic salmon stocked	500 000
Catchability	6.65×10^{-09}
Catchability variance	1.11×10^{-15}
Marginal value of Pacific salmon	\$16.43
Proportion of Pacific salmon angling value applied to Atlantic salmon	0.75
Variance in salmon value difference	0.05
Existence value of Atlantic salmon to Ontario	\$31 391 000
Existence value exponent	1.59×10^{-04}
Existence value scalar	3048
Existence value scalar variance	0.01
Total salmonid biomass	15 000 000 kg
Carrying capacity variance	0.001
Biomass to numbers Pacific salmon conversion factor	1.5
Coregonid recovery rate	0.1
Variance of coregonid recovery rate	0.25
Probability of EMS effect	0.5
EMS effect variance	0.5
Ricker alpha	3.89
Ricker beta	8.0×10^{-6}
Recruitment variance	0.04
Atlantic salmon stocking mortality	0.50
Probability of spawning at age 0	0.00
Probability of spawning at age 1	0.00
Probability of spawning at age 2	0.15

Continued.

Probability of spawning at age 3	0.35
Probability of spawning at age 4	0.75
Probability of spawning at age 5	1.00
Probability of spawning at age 6	1.00
Atlantic salmon natural mortality at age 0	0.70
Atlantic salmon natural mortality at age 1	0.40
Atlantic salmon natural mortality at age 2	0.20
Atlantic salmon natural mortality at age 3	0.20
Atlantic salmon natural mortality at age 4	0.20
Atlantic salmon natural mortality at age 5	0.20
Atlantic salmon natural mortality at age 6	0.20
Atlantic salmon weight at age 0	4.5×10^{-3}
Atlantic salmon weight at age 1	0.01
Atlantic salmon weight at age 2	1.00
Atlantic salmon weight at age 3	2.50
Atlantic salmon weight at age 4	2.00
Atlantic salmon weight at age 5	3.50
Atlantic salmon weight at age 6	3.90