GREAT LAKES FISHERY COMMISSION

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Managing Fish Translocation Risks Using Real Options:

Sea lamprey pathogen screening as a case study

by:

Eli Fenichel[2,3], Jean I. Tsao[2,4], Michael Jones[2,3] and Graham J. Hickling[5]

[2]Department of Fisheries and Wildlife, Michigan State University, East Lansing MI 48824

[3]The Quantitative Fisheries Center, Michigan State University, East Lansing MI 48824

[4]Department of Large Animal Clinical Sciences, Michigan State University, East Lansing MI 48824

[5]Department of Forestry, Wildlife, and Fisheries, University of Tennessee, Knoxville TN 37996

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ABSTRACT

This report, funded by the Great Lakes Fishery Commission, develops a bioeconomic framework for evaluation of Great Lakes disease introduction risks associated with sea lamprey translocations undertaken as part of the Sterile Male Release Technique (SMRT) program. The SMRT program is a component of the integrated pest management program for sea lamprey control in the St. Marys River, northern Lake Huron. Male sea lamprey are collected, sterilized, and released into the St. Marys River to compete with wild fertile males for female mates to reduce overall spawning success. The sea lamprey sterilized for the program mostly come from the upper Great Lakes, however some are brought into upper Great Lakes from Lake Ontario. Despite the demonstrated benefits of the SMRT program, there is concern that the translocating sea lamprey as part of the program could introduce new pathogens that might trigger disease outbreaks within the recreational or commercial fish stocks of the upper Great Lakes. Consequently, the Great Lakes Fish Health Committee currently recommends that samples of Lake Ontario sea lamprey be screened for pathogens prior to translocation. The appropriate extent – and thus necessary cost – of this screening program remains uncertain.

Our objectives were 1) to develop an analytical framework capable of integrating the potential costs of pathogen introduction *versus* the benefits of using Lake Ontario sterile male sea lamprey in the St. Marys River SMRT program; 2) to identify the analyses and data required for bioeconomic evaluation of the present sea lamprey pathogen screening strategy; and 3) to make general recommendations regarding the application of these kinds of bioeconomic analyses to other inter-lake fish translocation issues.

A review of the literature suggests that Real Options Analysis (ROA) provides a useful framework for decision making about risks associated with fish translocations. ROA is a form of benefit-cost analysis that can explicitly account for the tradeoff between the benefits and costs of the sea lamprey translocation. A key difference between ROA and traditional benefit-cost analyses is that ROA takes into account the uncertainty and irreversibility implicit in management action. For example, using ROA it is possible to include the risk and potential irreversible effects of pathogen transfer. Therefore, ROA is a precautionary approach that relates the degree of precaution merited to the uncertainty associated with the decision in general and pathogen transfer risk in particular. The result of an ROA analysis is a decision rule to either proceed with a program that is expected to provide benefits but may have irreversible consequences, or to delay the program and undertake further investigation of the situation so as to reduce uncertainty. As uncertainty is reduced it will become clearer whether the proposed program truly provides net benefits.

This report explains the ROA approach and outlines how it can be applied to decisions about the use of Lake Ontario sea lamprey as part of the St. Marys SMRT program. This report also illustrates the role a screening program can play in reducing the probability of pathogen translocation. A meaningful ROA analysis will explicitly consider the SMRT pathogen screening strategy, its influence on the likelihood of pathogen translocation, and its cost of operation.

For future work, we recommend the following:

- A necessary first step towards a real options analysis (ROA)- or any similar integrative, bioeconomic analysis - of the sterile male sea lamprey release program is to begin integrating current models of Great Lakes fishery management;
- A preliminary ROA should then be conducted on the sterile male sea lamprey release system, with particular emphasis on inclusion and examination of the screening component of the program;
- New field data will be required to help reduce uncertainties within the preliminary ROA (anticipated data needs are listed in the body of the report);
- Clarifying the relative importance of the various pathways by which pathogens could move between lakes should be considered a high priority;
- The Great Lakes Fishery Commission should consider adopting the analytical framework developed here when evaluating other fish translocation decisions.

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INTRODUCTION

Recreational and commercial fishers and conservationists value the unique Great Lakes ecosystem and are especially concerned with Great Lakes' fish stocks. Following the invasion of sea lamprey (*Petromyzon marinus*) in the 1930s, populations of lake trout (*Salvelinus namaycush*), whitefish (*Coregonus clupeaformis*), and other valued species declined (Smith and Tibbles 1980). Largely as a consequence of this invasion, the Great Lakes Fishery Commission (GLFC) was formed in 1955 and since then has led efforts to control sea lamprey populations. Initial efforts employing lampricides and barriers recently have been supplemented by an integrated pest management approach that includes sterile male release (Schleen *et al.* 2003).

The Sterile Male Release Technique

Many sea lamprey spawn in the St. Marys River, making the St. Marys River a major source of parasitic sea lamprey. Sea lamprey control undertaken in the St. Marys River includes the release of sterilized adult male sea lamprey that compete with wild fertile males to attract females, thereby reducing the reproductive output of the female population. Available evidence and computer modeling indicate that a high ratio of sterile to fertile males (around 7:1 when combined with other sea lamprey control methods) is necessary to the control of sea lamprey (Haeseker 2001). Consequently, managers go to considerable effort to obtain as many adult male sea lamprey for sterilization from as many sources as possible. The bulk of the collection comes from the upper Great Lakes (over 85 percent of male sea lamprey come from within 350 km of the St. Marys River; Bergstedt and Twohey 2005). Some male sea lamprey, however, are collected from Lake Ontario, sterilized, and then released into the St. Marys River (Fig. 1).

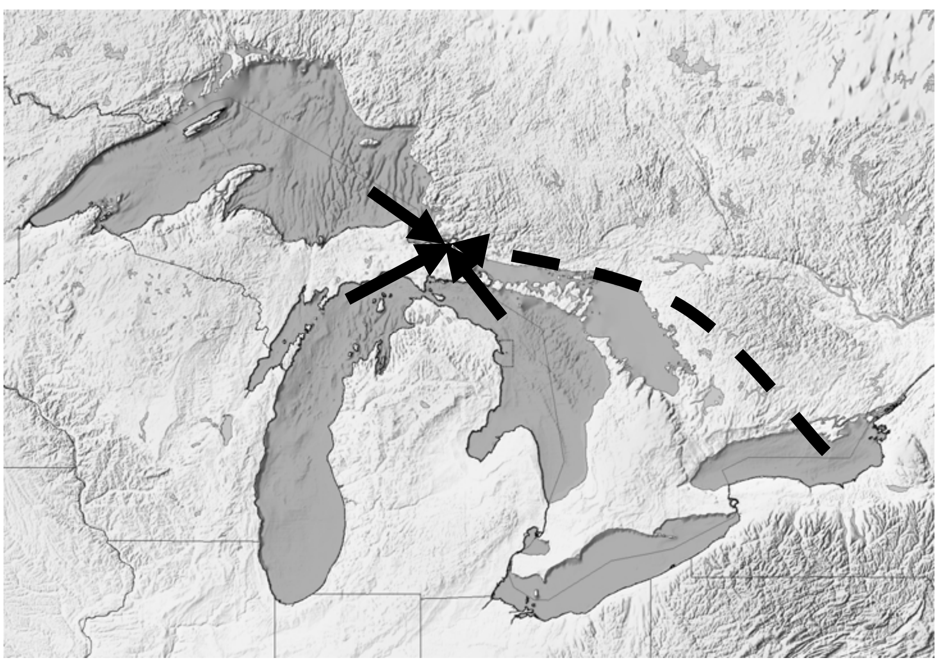

Figure 1. A map of the Great Lakes Basin illustrating sources of the male sea lamprey used in the sterilization program. The arrows represent the sources of sea lamprey sterilized and released into the St. Marys River. The dashed arrow, from Lake Ontario, represents the translocation of particular concern (background map from USGS).

This biological control program, referred to as the Sterile Male Release Technique (SMRT), appears to produce net economic benefits (Lupi *et al.* 2003). Nevertheless, there is growing concern that the use of Lake Ontario sea lamprey in the St. Marys River SMRT program could facilitate the transfer of pathogens that could trigger disease outbreaks within the recreational or commercial fish stocks of the upper Great Lakes (Bergstedt and Twohey 2005).

The Great Lakes Fish Health Committee's (GLFHC's) 'model program' guides pathogen management activities in the Great Lakes. A key objective of the 'model program' is to limit the spread of pathogens in the Great Lakes Basin. In this context, two pathogens are presently of particular concern. There is concern that *Heterosporis sp.*, a microsporidian parasite associated with percids, may spread from Lake Ontario to the upper lakes (Bergstedt and Twohey 2005). Furthermore, the agent of viral hemorrhagic septicemia (VHSv, Great Lakes variant), an RNA virus, is emerging in Lakes Ontario and Erie (Fish Health Committee Emergency Meeting Minutes 8/2006). During the spring of 2003, the GLFHC alerted the Council of Lake Committees to concerns about *Heterosporis* and recommended that live fish not be transferred from Lake Ontario to reduce the risk of spreading this parasite. On October 24, 2006, the United States Department of Agriculture Animal and Plant Health Inspection Service banned the interstate and international movement of many species of live fish from and within the Great Lakes region in an attempt to prevent the spread of VHSv (Rogers and Redding 2006).[1]

Sea lamprey translocation and the associated tradeoffs is a specific example of a general issue: species translocations can provide great benefits to society in terms of biodiversity restoration, restocking of over-harvested species, and biological pest control (Rondeau 2001) - yet moving organisms can also introduce pathogens that threaten ecosystems, industry, and human health (Daszak 2001). Well-intentioned transfers may, in the long run, cause unanticipated damage or conflict (Rondeau 2001).

Such tradeoffs are highlighted in this case by the concerns surrounding the use of Lake Ontario sea lamprey in the St. Marys SMRT program. Analysis of these tradeoffs requires Great Lakes fisheries managers to think beyond traditional disciplinary boundaries. The overall goal for Great Lakes managers is to maximize benefits associated with the Great Lakes fisheries, yet sea lamprey control managers tend to equate decreased sea lamprey populations with larger fishery-related benefits, while fish health officials equate lower disease risk with increase fishery benefits.[2] Given the trade-off between these two management activities, it is clear that a holistic perspective is helpful: the trade-off becomes readily apparent when the management outcome is discussed in terms of 'fisheries benefits', rather than in terms of either sea lamprey numbers or the probability of a disease outbreak.

Integrating screening into the SMRT program

In March 2004, the GLFHC reviewed plans for future transfers of sea lamprey from Lake Ontario and expressed concern about transfer of pathogens beyond *Heterosporis sp*.[3] The GLFHC presently favors a precautionary approach involving "maximum possible screening" and "minimum translocations" until "definitive studies on the risk of potential transmission" are completed (G. Christie, unpublished report).

[1] The sea lamprey currently is not considered a susceptible species, so movement of live sea lamprey is not currently prohibited. However, import of all live fish from Ontario and Quebec, Canada is prohibited so transportation routes and capture sites on the Canadian side of Lake Ontario may be restricted.

[2] Formally, the GLFC states that one of its two major responsibilities is '…to recommend measures which will permit the maximum sustained productivity of stocks of fish of common concern.' We understand this as to mean that the GLFC seeks to maximize benefits associated with fish stocks of common concern, some of which may provide non-consumptive values. We recognize that fish community objectives, articulated by Lake Committees under the Joint Strategic Plan for Management of Great Lakes Fisheries, are commonly used to achieve this aspect of its mission.

[3] Great Lakes managers considered the use of Atlantic sea lamprey, but never proceeded with the program due, in part, to concerns about the possibility of pathogen transfer from the Atlantic to the Great Lakes (G. Christie pers. comm.).

Great Lakes managers are also considering translocations of species other than sea lamprey, and samples of these fish would be screened before being moved between lakes (G. Wright pers. com). Screening is presently not required for sea lamprey moved among the three upper lakes (for SMRT and assessment studies), as sea lamprey are believed to move naturally among these lakes (G. Christie, unpublished report).

The screening program utilizes staff resources and funds that could otherwise be used ton translocate additional sea lamprey or on other management activities. Thus the screening program is costly. The appropriate extent – and thus necessary cost – of this screening program is subject to ongoing debate, in part because almost no work has yet been done on how best to manage the future risk of invasion of novel pathogens into wild fish populations. A framework is needed that will allow managers to integrate and evaluate *i)* the increased risk of disease outbreak; *ii)* the effort and resources required to undertake sea lamprey disease screening to mitigate against that risk; and *iii)* forgone opportunities to achieve more productive recreational and commercial fisheries expected through improved effectiveness of SMRT (Fig. 2).

Prompted by managers' requests for guidance on the appropriate level of resources to allocate to the SMRT screening program, we report on a bioeconomic framework that allows the costs and benefits of the SMRT program to be considered jointly. This framework has broad application to other fish translocation decisions and disease issues in the Great Lakes.

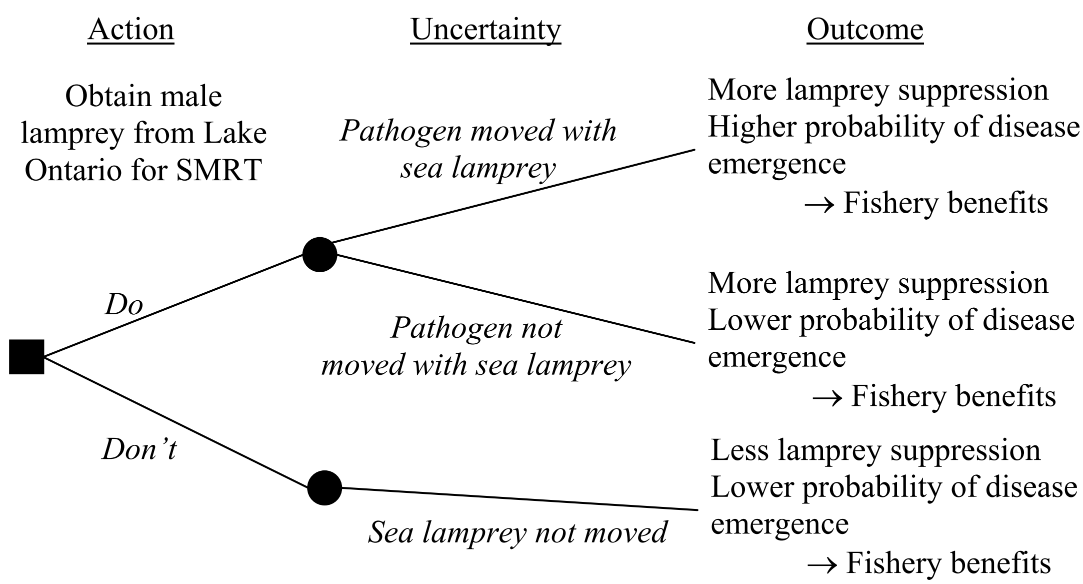

Figure 2. A decision tree illustrating the decision possibilities (represented by the square node), a key source of uncertainty (represented by the round nodes), and potential outcomes. This figure emphasizes that tradeoffs emerge in areas typically not measured in the same units (i.e. lamprey suppression and disease emergence). The question that needs to be addressed is: how do sea lamprey numbers and disease risks interact to affect fisheries benefits?

Why do we need a bioeconomic framework?

Economic and ecological systems are often jointly determined – that is, human choices affect the state of ecological systems, which has economic consequences (Sanchirico and Wilen 2001; Shogren *et al.*1999). Models can be useful in understanding this 'joint determination' and analyzing tradeoffs that emerge. Recently, such thinking has been applied to the impacts that management practices have on invasive species (Finnoff *et al.* 2005; Horan *et al.* 2002; Olson and Roy 2002; Saphores and Shogren 2005).

SMRT sea lamprey screening provides a case study of a situation in which numerous uncertainties surround the jointly determined ecology and economics of the program. For example, the influence of human activities on the probability of pathogen transfer and subsequent disease outbreak among populations of fish in the Great Lakes is poorly understood. Moreover, it is not well understood how people value various fish species and how pathogens may affect these values. Therefore, the impact of a disease outbreak on the value of Great Lakes fisheries remains uncertain. The social value of increasing the lake trout population, the fish most often parasitized by sea lamprey, is also unknown.

A further complication is that the occurrence of diseases in the wild fish in these lakes is neither well documented nor regularly monitored. Similarly, it is unclear which fish pathogens are established in which lakes (M. Faisal, pers. comm.), although it is assumed that each lake has a distinct pathogen community, whereby some pathogens are present in most lakes while others are less widespread. Lastly, some pre-existing natural and/or anthropogenic routes of pathogen transfer exist between lakes in the system (e.g., Fig. 3).

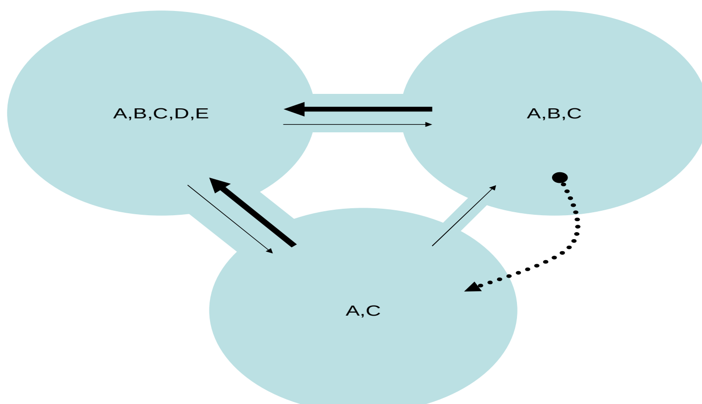

Figure 3. Pathogen community connectivity in a hypothetical three-lake pathogen system. Each lake has a unique assemblage of pathogens (the letters indicate different pathogen); however few are unique to a single lake (e.g., pathogen A is ubiquitous throughout the system, whereas pathogen C is present in two of the three lakes). Natural and/or anthropogenic transfer of pathogens may occur between lakes, although the likelihood of translocation is usually higher in one direction than in the other (indicated by the widths of the respective arrows). The challenge is to understand the consequences of superimposing upon these pre-existing pathogen assemblages and transfer probabilities an additional transfer probability associated with fish translocations (indicated by the dashed line).

The current sea lamprey transfer protocol is not cost-free; the optimal investment in disease surveillance, however, is unclear. The current level of surveillance may not be the most cost-effective. A lack of data and integrated systems thinking has hampered evaluation of the tradeoffs between the benefits and costs of the current program (G. Christie, pers. comm.). It is also important to recognize that the screening program for use of Lake Ontario sea lamprey in the St. Marys SMRT program is one component of a larger resource allocation system (Fig. 4). Managers face the question: how best to invest scarce resources to achieve overall lake management objectives? We suggest that this question is best addressed through the development of a quantitative bioeconomic framework for the system.

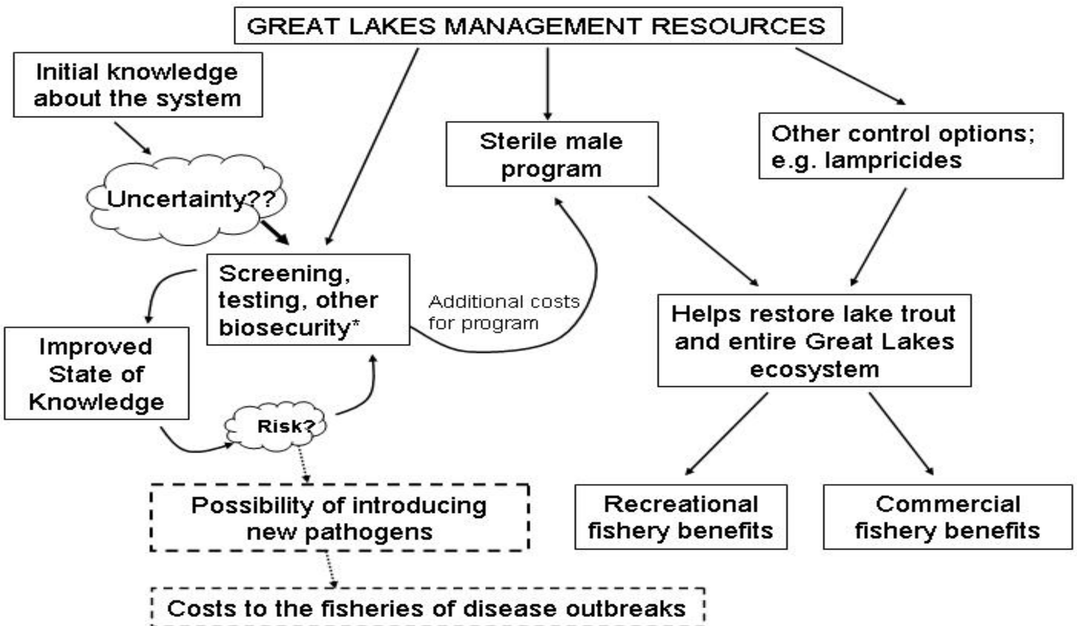

Figure 4. A conceptual model of the resource allocation decision associated with sea lamprey control in the Great Lakes, incorporating current concerns that there may be disease introduction risks associated with the current sea lamprey SMRT program.

Costs and benefits in quantitative decision-making

Fisheries managers have traditionally employed fish translocations to help improve fish stocks or develop new fisheries. Recent concerns about genetic stocks, biodiversity, disease, and exotic species have made managers increasingly aware of the 'nonuse value' and 'ecosystem services' provided by native aquatic fauna and of the potential negative consequences of fish translocations. Therefore, it is important that *both* the benefits *and* the costs of a translocation decision are evaluated: the mere existence of benefits from a potential translocation does not justify going forward with the translocation, while the mere existence of costs or risk should not prevent the translocation.

Managers already consider – qualitatively - the benefits and costs of fish translocations. Nevertheless, adoption of quantitative decision making techniques will enable fisheries managers to more clearly communicate and defend the decisions they make. Formal analysis of decisions allows alternative view points to be treated as hypotheses, integrated, and weighed according to support from data or expert opinion. These techniques help decision makers make difficult decisions in the face of uncertainty by clearly highlighting the sources of uncertainty and the tradeoffs associated with exposure to competing risks.

When managers adopt a more quantitative decision making approach, it is vital that they have a clear understanding of what is meant by the 'costs' and 'benefits' of a decision. Marginal *benefits* of a decision are the gains associated with making one decision as opposed to another. The relevant measure of benefits when exploring alternative policies is the change in 'consumer surplus' to stakeholders (see Hoehn *et al.*1996 for a full discussion of this concept). To obtain a particular good or service, the consumer surplus is the difference between how much people are willing to pay and how much they actually must pay. For example, for a given level of fishing service from the lake, the consumer surplus would be how much citizens of the Great Lakes Basin would be willing to pay for that level minus how much they actually must pay (i.e., expenditures on fishing trips, donations to conservation organization, and so on).

Costs are forgone opportunities associated with a decision. Clearly, the forgone opportunities associated with one decision are benefits from the next best alternative decision. In the context of transferring sea lamprey from Lake Ontario as part of the sterile male release program, the costs of the translocation are the forgone benefits to the program of not bringing in the sea lamprey from Lake Ontario. For example, reduced risk of disease is a benefit of not translocating sea lamprey, and thus increased disease risk is a cost if sea lamprey are transferred.

In this situation, the appropriate measure of net benefit would be the difference between the consumer surplus if the translocation did occur and the consumer surplus if it did not.

Risk, uncertainty, and the 'precautionary principle'

Investments in natural resources should be undertaken when the benefits from the investment seem likely to exceed the costs. However, just as with any other investment, natural resource investments are not risk-free. That is, for a given decision there is always a range of possible outcomes, some more likely and/or better for society than others.

The importance of uncertainty in fisheries and ecosystem management is becoming well-accepted (Hilborn and Walters 1992). Uncertainty is a lack of knowledge or imperfect information about how systems work. Natural resource management decisions carry risk because uncertainties about biological and socio-economic systems affects the outcomes that society experiences. Moreover, perceptions of risk affect the decisions made. Therefore, the term 'uncertainty' denotes a lack of scientific information. The term 'risk' describes the distribution of potential outcomes that are conditional on both uncertainty and on managerial decisions (Shogren and Crocker 1999). Therefore, it is not possible to separate the roles of risk assessment and risk management (Maguire 2004).

One approach to managing risk has been to invoke the 'precautionary principle' (Peterson 2006). The precautionary principle effectively says, 'if there is risk, don't do it.' The precautionary principle is stated more formally the Rio Declaration; projects should not be untaken where there are "threats of serious or irreversible damage or lack of full scientific certainty" (UNCED 1993). However, the precautionary principle does not help managers make risk exposure decisions when there is a chance of adverse consequences associated both with enacting and also with forgoing a program (Farrow 2004). The precautionary principle also fails to value the opportunity to reduce uncertainty (since it requires that uncertainty and risk be eliminated entirely - a condition that is unlikely to be met; Prato 2005). A final short-coming of the precautionary principle is that it ignores completely the forgone benefits associated with accepting some degree of risk. Given these short comings, Peterson (2006) argues that the precautionary principle can not be considered a true decision rule, but may be valuable as an 'epistemic principle' for shifting the burden of proof.

Standard quantitative investment frameworks provide a way to structure thinking about project uncertainties (Alessandri *et al.* 2004). For example, simplistic application of the precautionary principle would lead Great Lakes fisheries managers to halt all future fish translocations, whereas investment frameworks can provide a more sophisticated approach that can help determine, *how much risk is acceptable given an objective*? Miller and Waller (2003) and Alessandri *et al.* (2004) show how quantitative decision making frameworks also can be used qualitatively to help organize thinking about organization or system level risk. Specifically, these frameworks can be used to take a precautionary approach in a way that balances the costs of risk with the costs of forgone opportunities (Farrow 2004; Morel *et al.* 2003).

There is uncertainty associated with the decision to transfer sea lamprey; future benefits and costs are uncertain, and such uncertainty needs to be accounted for. In the later sections of this report, we identify a suitable framework for balancing these benefits, costs and risk.

OBJECTIVES

In preparing this report, our objectives were:

- To develop an analytical framework capable of integrating the potential costs of pathogen introduction *versus* the benefits of using Lake Ontario sterile male sea lamprey in the St. Marys River SMRT program;
- To identify the analyses and data required for bioeconomic evaluation of the present sea lamprey pathogen screening strategy;
- To make general recommendations regarding the application of these kinds of bioeconomic analyses to other inter-lake fish translocation issues.

METHODOLOGY

This report is based on the following activities:

- We reviewed the current literature on the bioeconomic assessment of costs and benefits in the case of uncertainty and irreversible decisions in general, and decisions associated with invasive species management, emerging disease outbreaks, and species translocations in particular. This review considers the benefits and costs of outcomes and impacts as well as the benefits and costs of achieving and avoiding such outcomes and impacts.
- We communicated with key individuals involved in sea lamprey translocation and disease screening activities to gather available data and to ensure correct formulation of the analytical framework.
- We developed a risk assessment/management framework focused on the probability and potential impact of disease introduction through the transfer of sea lamprey and/or other wild fish based on the findings of our literature review, meetings, and discussions.

We have outlined steps for the implementation of our proposed framework. These steps include recommendations on gathering and integrating prior work and data. Additionally, we highlight needed information that is currently unavailable and recommend approaches that will enable managers to learn more about the system and thereby reduce uncertainties.

RESULTS

An analytical framework for integrating the benefits, costs, and uncertainties of the Lake Ontario - St. Marys River sea lamprey SMRT translocation

Traditional benefit-cost analyses: approaches and limitations

A fisheries management decision is an investment decision in natural resources, which are a form of capital. It is therefore appropriate, to use tools designed to value capital investments to inform fisheries management decision making.

Benefit-cost analyses commonly are conducted to inform natural resource management decisions. Indeed, sea lamprey control has been previously justified on the basis of benefit-cost analysis (Stewart *et al.* 2003). The simplest such decision-making approach simply states that decision makers should proceed with a project when the benefits outweigh the costs:

(1) Proceed with program if: Benefits – Costs ≥ 0

In this case, benefits can be thought of as the net benefits from advancing a project (e.g. translocating sea lamprey) and costs can be considered the net benefits without the project (e.g. a St. Marys River SMRT program with no transfers of sea lamprey from Lake Ontario).

Another way of interpreting equation (1) is that the *marginal* benefits gained by translocating sea lamprey must be at least equal to zero. The decision rule formalized by equation (1) is the 'net present value (NPV) rule' for capital investment, since future benefits and costs are first converted to present value through a discounting process, and then the program proceeds if the net value is positive. Discounting helps account for time preferences, that is the desire to have benefits today and pay costs tomorrow (Conrad 1999). The NPV rule, which can be illustrated with a decision box (Fig. 5), is an appropriate decision-making framework *provided* there is no uncertainty and/or the decision is completely reversible.

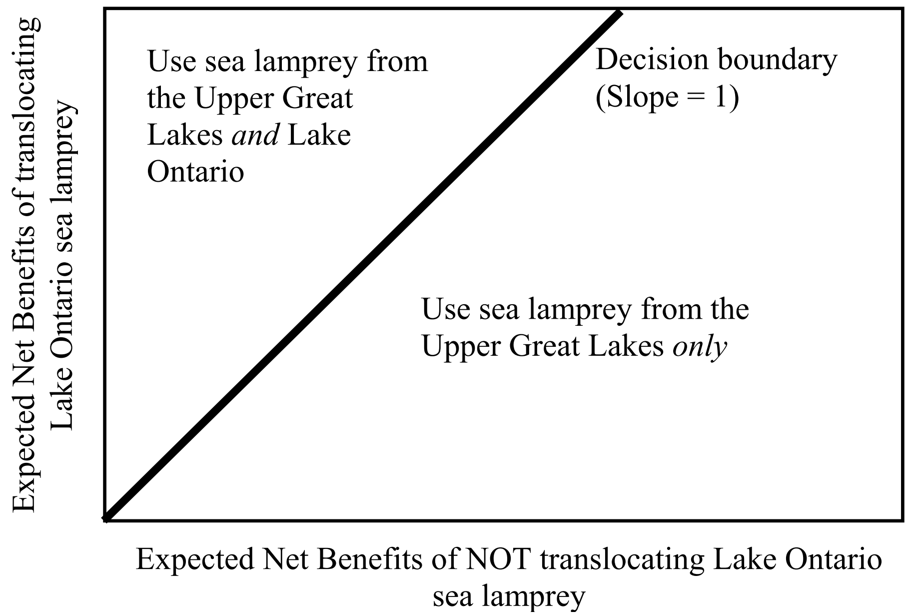

Figure 5. A decision box illustrating how the decision to include sterilized male sea lamprey from Lake Ontario as part of the St. Marys SMRT program would be evaluated under the NPV rule. When the best estimate of the relative benefits falls below and to the right of the decision boundary, only sea lamprey from the Upper Great Lakes should be used in the St. Marys SMRT program. Lake Ontario sea lamprey should be included in the program only when the best estimate of the relative benefits fall above and to the left of the decision boundary.

In the context of sea lamprey translocations the NPV is inappropriate; it underestimates the cost of uncertainty by implicitly assuming that the project being evaluated is reversible (Dixit and Pindyck 1994). Yet, some outcomes of a translocation may be irreversible; for example, the introduction of a new pathogen into the Upper Great Lakes. Additionally, the resources used in the project can not be recovered and represent another source of irreversibility (this is especially important if there is uncertainty that the project will achieve objectives). Some attempts have been made to modify the NPV rule by adjusting the discount rate to account for risk.[4] However, a risk-adjusted discount rate cannot be calculated accurately when calculated independently of the identification of the optimal decision, because management

[4] The NPV rule has been modified to consider risk by incorporating a risk-adjusted 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 observe the 'price of risk' by observing the rate of return earned by similarly risky projects. However, natural resource management decisions are often so unique that any such comparison is problematic. There is no generally accepted way to price risk for public projects and indeed risk often remains unpriced when public projects are evaluated (van Ewijk and Tang 2003; Lesser and Zerbe 1994).

decisions and management flexibility alter risk characteristics (Copeland and Antikarov 2003; Brandao *et al.* 2005a).

When future benefits are uncertain and/or irreversible, a ‘precautionary’ approach is more appropriate (Conrad 1999). A precautionary adjustment (PA) needs to be applied between the benefit and costs (Dixit and Pindyck 1994 p. 142), so that the decision rule becomes:

(2) Proceed with program if: Benefits – Costs > PA > 0

The notion of a PA is implicit in two decision approach the ‘precautionary principle’ and the ‘minimum safe standard’ (Prato 2005). In both approaches, the size of the PA is chosen arbitrarily: in the case of the precautionary principle it is set at infinity (Figure 6). Peterson (2006) argues that given the arbitrary nature of these approaches they are inconsistent with rational decision theoretic.

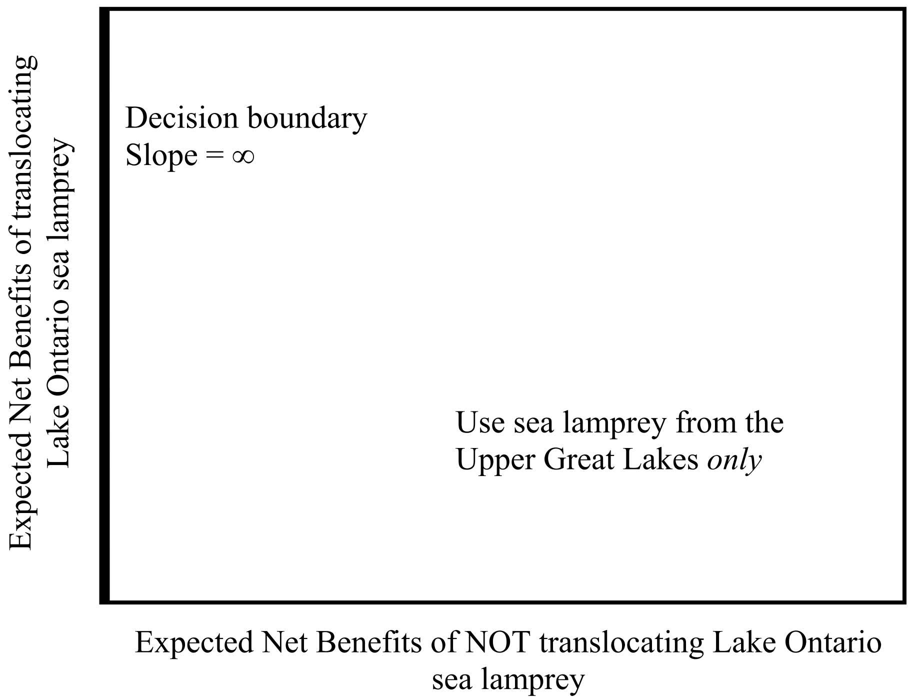

Figure 6. A decision box illustrating how the decision to use sterilized male sea lamprey from Lake Ontario as part of the St. Marys SMRT program would be evaluated under the ‘precautionary principle’. Note that the slope of the decision boundary is set equal to infinity, regardless of the nature or extent of uncertainty about the system. Under this approach, the best estimate of the relative benefits of the program always falls to the right of the boundary, so sea lamprey from Lake Ontario should never be transferred.

The ‘minimum safe standard approach’ is less extreme than the precautionary principle. That is, the PA is chosen to be some arbitrary value greater than one and less than infinity. The problem with this approach is that the PA is chosen arbitrarily, rather than in a way that couples the level of uncertainty with the size of the PA. The minimum safe standard approach thus may adopt a PA that is too large or too small.

The PA can be thought of as the cost of making the decision with imperfect information or the cost of giving up the ability to make a better decision in the future with better information. In this approach, the terms in Equation 2 are rearranged so that the PA is more easily recognized as a cost (Equation 3). That is, the PA creates a “hurdle” that the benefits must overcome to outweigh the costs:

(3) Proceed with program if: Benefits – (Costs + PA) > 0.

Ideally, the PA would be calculated based on the level of understanding and uncertainty about the system. The standard frameworks for NPV and minimum safe standard provide no guidance on calculating a PA that is coupled with the level of risk, which leads to arbitrary judgments. Consequently, managers may exercise inadequate precaution or forgo beneficial management actions, both of which are in fact costs to the program and society.

Simulation approaches to decision analysis that can incorporate uncertainty

The need to explicitly include uncertainty in decision making has led to using approaches based on stochastic, Monte Carlo simulation. These techniques involve developing mathematical models of the system 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. Decision analysis is a popular way to analyze the outputs of these stochastic simulation models. Peterman and Anderson (1999) provide an 8-step approach to decision analysis:

1. Clearly state the management objectives;
2. Clearly state the management possibilities;
3. State uncertainties about the state of nature;
4. Assign probabilities to the uncertain states of nature;
5. Develop models to calculate the outcomes associated with each management option;
6. Develop a decision tree;
7. Rank management options;
8. Conduct sensitivity analyses.

The decision analysis approach provides a useful way of identifying decision possibilities and sources of uncertainty. It can also be used to prioritize research. To evaluate a decision, Peterman and Anderson (1999) state that each combination of outcomes should be valued using the NPV rule, with the analyst working backwards, in recursive fashion, on the decision tree. This works well for simple problems. Stochastic dynamic programming works in a similar fashion, and may be used to efficiently find optimal solutions for moderately complex decision trees. However, decision trees and stochastic dynamic programming may be infeasible due to computational limitations when there are multiple sources of uncertainty.

A number of *ad hoc* alternative approaches have been developed to avoid the complexity of the stochastic dynamic programming. Brandao *et al.* (2005a) consider these approaches to be naïve because the proper discount rate for a project should include a risk premium, but the risk characteristics of the project change when flexibility is incorporated into the project valuation. As stated above, calculating the risk premium is problematic since the risk is an endogenous function of decisions. Decision analysis is a powerful tool to help understand the sources of uncertainty in a system, the potential outcomes of different management actions, and prioritizing future research. Decision analysis, however, is less helpful in determining the size of a PA, or locating a decision boundary for complex problems.

Real Options Analysis

Options analysis extends decision analysis and adds a powerful tool that allows the calculation of a PA based on the characteristics of the system and the state of knowledge.

Definition 1. *Option:* the right, but not the obligation, to do something

When using an options analysis approach, it is useful to rephrase the question from "Should we take action X?" to, "When should managers exercise the option that they hold to initiate action X?"[5] One

[5] All the options discussed in this report have no expiration date, as is commonly the case with natural resource management options. In contrast, business options often do expire.

appealing aspect of using on options approach is the manager no longer delays the decision for more information (implicitly making a decision), but decides either to go ahead with a program or to wait for more information, and thereby delaying the program's start. The difference is subtle, but the manager is being explicit about the decision being made in the latter situation. It should be noted that in the jargon of options, the manager never decides *not* to initiate a program, but rather decides to keep holding the option - perhaps indefinitely. The option to implement the program, however, always remains.

High levels of uncertainty create an incentive to hold the option. As uncertainty is reduced, the manager may learn that the program will not provide adequate benefits. In this case the value of the option becomes zero and the manager may 'scrap the option' or make a 'final decision' since the option to make a 'bad' decision is trivial. Options are only important in the case where *i)* expected marginal benefits from the project are positive, and *ii)* there is uncertainty, as indicated by a positive PA (Table 1).

Table 1. Matrix of appropriate decision rules. PA = precautionary adjustment.

PA	Expected Marginal Benefits		
	< 0		> 0
= 0 (no uncertainty)	Evaluate project with *Net Present Value rule* and *reject* project		Evaluate project with *Net Present Value rule* and *proceed* with the project
> 0 (uncertainty exists)	Evaluate project with *Real Options Analysis,* If costs > benefits *reject* project	Evaluate project with *Real Options Analysis* If the PA + costs > benefits *hold* the option	Evaluate project with *Real Options Analysis* and *exercise* option

The kind of option we are referring to is known as a 'real option' (as opposed to a *financial* option such as a stock option). Real options analysis (ROA) was specifically developed to analyze investment decisions when *i)* the decision is to some extent irreversible, and *ii)* where there is the opportunity to delay making the investment until more information in gained (Dixit and Pindyck 1994). Real options differ from financial options in that real options do not require as much precision as financial options, since the objective of ROA is to inform broad decision making under uncertainty and irreversibility, as opposed to creating leverage for marginal gains (de Neufville 2001). ROA provides a quantitative framework where the 'precautionary' adjustment is endogenously determined as a function of the risk associated with the decision (Farrow 2004).[6] ROA accounts for the added value of being flexible and waiting for some uncertainty to be resolved (this has been called the 'option value' in the capital investment literature and the 'quasi-option value' in the resource economics literature – see Fisher 2000). Most importantly, ROA provides a means to calculate the size of the PA that should be added to the cost of a decision; thus it is an improvement over traditional benefit-cost analysis and the minimum safe standard approach. It extends decision analysis by providing the utility of a capital investment approach that gives a decision rule, even when there are multiple sources of uncertainty.

The PA is calculated in the form of a precautionary multiplier (Γ) that is based on the characteristics of the system in which the option exists (Farrow 2004).[7] The simplest way to characterize a program resulting from a decision is by the best estimate of benefits resulting from that decision, B_i, where i indexes the decision. The multiplier accounts for the additional risk of exercising the option (i = X), relative to holding the option (i = H). When program X carries no additional risk, it should proceed

[6] Prato (2005) draws comparisons between option value and the precautionary principle. However, Prato notes that the application of the precautionary principle tends to close options rather than placing a value on the option to act optimally in the future. The important distinction is that when ROA is applied it is still possible to make an irreversible decision when there is a 'lack of full scientific certainty,' a condition that will almost always exist.

[7] The mathematical details are discussed in Appendix 9.1.

provided $B_X / B_H \geq \Gamma = 1$. When program X does carry risk, the requirement to proceed becomes $B_X / B_H \geq \Gamma >> 1$. Perfect information or complete reversibility implies $\Gamma = 1$, and the NPV rule emerges (Table 1); as Γ increases, more precaution is needed. It is easy to express the PA exactly as:

(4) PA = Costs*(Γ - 1).

Conveniently, Γ is also equal to the slope of the decision boundary in the decision box (Fig. 7).

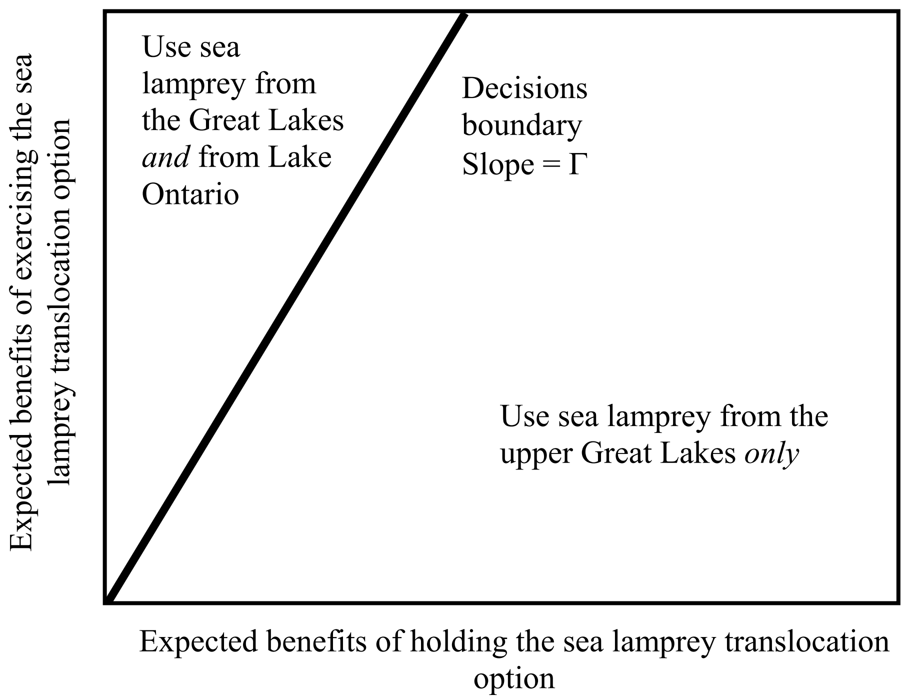

Figure 7. A decision box illustrating how the decision to use sterilized male sea lamprey from Lake Ontario in the St. Marys SMRT program would be evaluated using ROA. The axes have changed slightly to reflect the way we think about the decision; however this change is purely heuristic. As in the NPV case, when the best estimate of the relative benefits fall below and to the right of the boundary, only sea lamprey from the Upper Great Lakes are used in the St. Marys SMRT program. When the best estimate of the relative benefits fall above and to the left of the boundary, sea lamprey from Lake Ontario transferred to St. Marys as part of the SMRT program. Unlike the NPV, minimum safe standard, and precautionary principle cases, the decision boundary is determined by the nature of the uncertainty and risk associated with the decision to exercise the option.

The real option approach is increasingly being used in strategic firm management (Alessandri *et al.* 2004; Miller and Waller 2003). Triantis and Borison (2001) provide a review of its use in business. A number of authors have used ROA to provide a theoretical framework for natural resource management decisions in areas such as forest planning (Yin 2001), wilderness preservation (Conrad 2000), invasive species management (Saphores and Shogren 2005), air pollution reduction (Farrow 2004), and mine operations (Martzoukos 2000).

Managers of wild populations are often concerned with being 'adequately risk averse' (Regan *et al.* 2005). This concern is understandable, given that they have lacked a technique that allows calculation of a decision boundary based on the uncertainty and irreversibility in the system. Smith *et al.* (1999) question the role of managers as risk averse decision makes in their analysis Australia's 'weed risk assessment system' (WRA), used for deciding when to admit plants into the country. They retrospectively examined if weed introductions would have taken place had the WRA previously been in place. Under their best-case scenario, the probability of weed introductions declines from 2% to 0.36%, preventing 17 weeds and allowing three. However, the system would have also prevented the introduction of 147 or 15% of the beneficial plants introduced, and nine out of ten plants rejected could have been beneficial. Smith *et al.* (1999) state:

> *While this might be acceptable to environmentalists operating under the precautionary principle, it may not be acceptable to those seeking to introduce species for economic development. Regulators need to reconcile these conflicting aims.*

When the goal is to maximize benefits for the overall system, it may be more appropriate for the manager to be risk-neutral since a benefit to one stakeholder may be a loss to another and since uncertainty can result in windfalls as well as unanticipated losses. The PA calculated using ROA is generally independent of risk preferences (Dixit and Pindyck 1994; Morel *et al.* 2003).

ROA is related to the decision analysis technique presented by Peterman and Anderson (1999) and Cohan *et al.* (1984). Indeed, the main limitation of decision analysis is in dealing with multiple sources of uncertainty and complex systems. Brandao and Dyer (2005) emphasize that when applied correctly, decision analysis and ROA will give the same result. Smith (1999) and Branao *et al.* (2005a) differentiate ROA from decision analysis in that the latter emphasizes modeling the *sources* of uncertainty, whereas ROA emphasizes modeling the *dynamics* of the uncertainty. Another perspective is that decision analysis *characterizes the sources of uncertainty* and their effects on potential decisions, whereas ROA helps *determine a decision boundary* and optimal risk exposure. Consequently, it can be advantageous to combine decision analysis and ROA into an integrated framework that is capable of modeling both the sources and dynamics of uncertainty, to produce a decision boundary that guides decision making in the present and provides analysis to direct future research. The difference between the expected value of the decision selected using a real options approach *versus* the decision that would be made under the NPV rule is the value of information (Morel *et al.* 2003, but see Fisher 2000; Mensink and Requate 2005 for a complete analysis of the relationship between real options and the value of information).

Conducting Real Options Analysis

We recommend six general steps to implementing ROA in natural resource decision making. The first steps should be familiar to managers who have previously participated in decision analysis. ROA can be integrated into the eight steps for decision analysis proposed by Peterman and Anderson (1999) previously discussed.[8] The six steps are:

1. Defining and clearly stating the objective
2. Clearly defining the option
3. Developing models to simulate the effects of uncertainty and the decision to hold/exercise the option
4. Using the model to estimate the drift and volatility of outcomes
5. Calculating a precautionary multiplier to evaluate the decision
6. Making a decision

Begin by carefully formulating the objective. A common objective is to maximize the benefits associated with a resource, such as the fishery. The difficulty at this step comes in deciding how to weigh the surplus gained by different stakeholders; it is acknowledged that such decisions will be 'political' rather than the product of objective analysis (Arrow 1963 cited in Schmid 2004 p. 86).

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[8] As already noted, care must be taken when constructing decision-event trees. Peterman and Anderson (1999) do not describe this in detail; instead see Copeland and Antikarov (2003) or Brandao *et al.* (2005a).

The second step – defining the option – may also be difficult in that it requires managers to correctly identify the option that they currently hold[9]. The option is to make an irreversible decision. In our example the 'option to wait' is easily confused with the 'option to use the Lake Ontario male sea lamprey in the St. Marys River SMRT program.' Using the phase "the right, but not the obligation to …" can help. Thus, for the example, the option would be phrased:

Managers have the right, but not the obligation, to use male sea lamprey from Lake Ontario in the St. Marys River SMRT program.

In Step 3, models (i.e., competing hypotheses) about the system are developed and parameters are estimated from the available data. This allows the analyst or manager to model what is known, together with the sources of uncertainty. It is important to remember that when parameters are estimated, an estimate of their residual (i.e., unexplained) variance is also generated. From the perspective of decision making, these residual variance components are just as important as the parameter estimates themselves, since the former are actually additional parameters that characterize the state of (un)certainty about the system being modeling.

The strength of ROA is as an aide to decision-making 'today', based on today's data and uncertainty. Therefore, poorly-fitting models with large residual variance should not be thought of so much as 'problems,' but rather as a consequence of the poor state of knowledge (i.e., ignorance) about the system. This is because managers are comparing two decisions - both of which carry uncertainty and thus risk (in terms of outcomes for society).

As relative uncertainty increases, so too does the value of the option; that is, it becomes increasingly advantageous to wait until uncertainty has been be reduced (Copeland and Antikarov 2003, p. 87). Some systems may, however, be highly uncertain *regardless* of the decision to hold or exercise the particular option, and in which case, we would say that the decision itself does not carry risk. In our example, this could be the case if the uncertainty in the benefits associated with SMRT were driven mostly by, forage fish recruitment - not having to do with sea lamprey translocation at all. If that were so, benefits experienced by society from the sea lamprey translocation would continue to be highly uncertain regardless of the decision to hold or exercise the option to use male sea lamprey from Lake Ontario, and thus, our decision would carry little risk.[10]

Once a system model has been developed and coded into a computer, managers and analysts can use simulation procedures to generate model data on the benefits of the program under paired scenarios, where the option is either exercised or held. For decision analysis to account for uncertainty, a distribution of outcomes would be generated and the decision makers would make a single decision based on that distribution. ROA differs from decision analysis in that ROA can guide a decision, accounting for uncertainty, for each pair of simulations (one exercising and one holding the option). Multiple pairs of simulations can be conducted to account for uncertainty in the decision boundary. The solid lines in Figure 8 illustrate the potential change in benefits over time from a single paired hypothetical simulation where X is exercising the option, and H is holding the option.

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[9] Farrow (2004) points out the way the objective is defined - and specifically how surplus is weighed - affects the formation of the option.

[10] This clearly illustrates the difference between risk and uncertainty. Any future event for which the outcome is not perfectly known is 'uncertain', since uncertainty reflects our state of knowledge. Indeed, risk of a bad outcome also persists, but the risk is not associated with the decision. A decision only carries risk if some action may be taken to alter the probabilistic nature of such an outcome or the consequences of an event. Morel *et al.* (2003) point out that under such circumstances the optimal decision is indeed reached by application of the NPV rule.

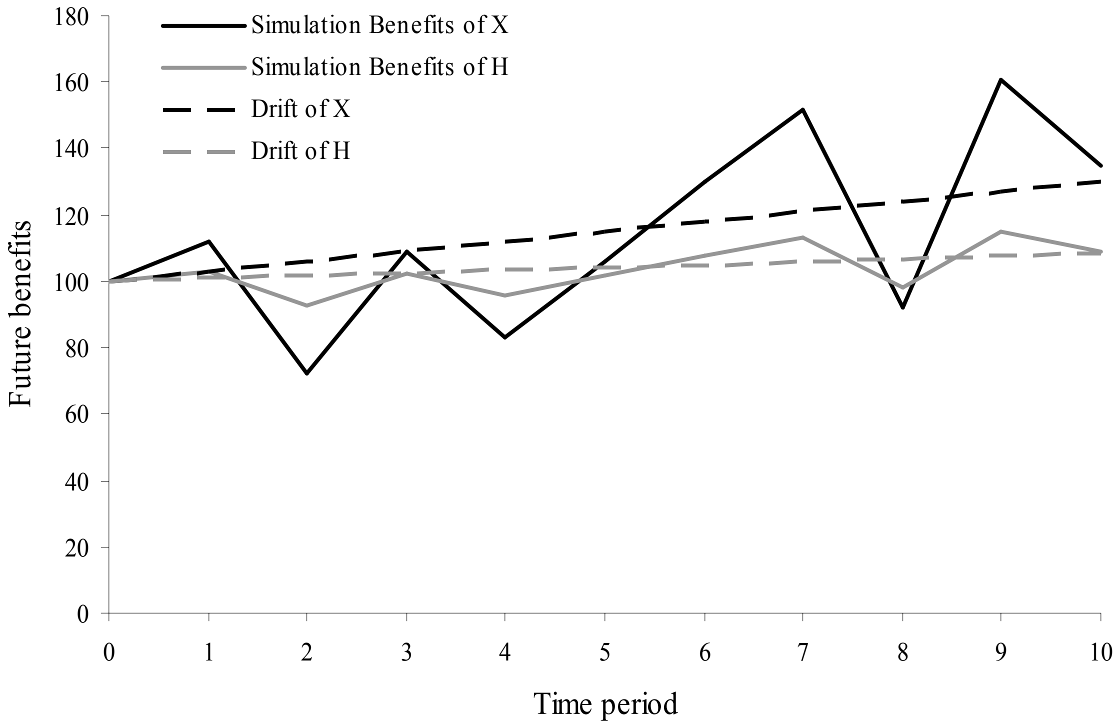

Figure 8. Predictions of future benefits, resulting from two hypothetical simulations. The solid black line is the path of the benefits over time from exercising the option. The solid grey line is the path of benefits from holding the option. The dotted lines represent the drift associated with the two decisions respectively.

In order to calculate Γ, the drift and volatility must be calculated for each paired simulation. Drift may be thought of as the general direction and magnitude of the change in benefits over time (i.e., the dotted lines in Figure 8). Alternatively, drift can be thought of as the expected result or the expected percent growth in benefits over time. Volatility is an estimate of the 'risk' associated with the outcome of a decision. It may be thought of as the difference between the observed change in benefits between time periods and the expected change in benefits between time periods. Estimation of these parameters is based on a time-series approach. In Figure 8, decision X has a larger drift and higher volatility than H. Formulas for calculating drift and volatility from simulation data are provided in Appendix 9.1. In addition to estimates of drift and volatility, a discount rate is needed for calculation of the precautionary multiplier; sensitivity analysis should be undertaken on the discount rate that is chosen.

The precautionary multiplier for a simple infinite horizon option is calculated by solving for a function to maximize the expected difference between the net benefits associated with exercising and holding the option.[11]

The mathematical details of this kind of problem have been well addressed elsewhere (see Dixit and Pindyck 1994 p 207; Morel *et al.* 2003) and will not be addressed here, although we do provide formulas sufficient for implementation in Appendix 9.1. The expected difference between the net benefits is maximized by a formula that depends on the drift and volatility estimates of paired simulations (holding and exercising the option), the correlation between the volatilities, and the risk-free discount rate. The

[11] The term 'simple' is not used in the sense of a simple problem, but rather refers to holding only one option as opposed to multiple options (sometimes called 'rainbow options'). 'Infinite horizon' means that the option does not expire or that the option to translocate sterilized male lamprey exists indefinitely.

precautionary multiplier, Γ, is set in a way that makes society indifferent between the expected gains of holding the option and exercising the option, given the relative risk of holding and exercising the option.[12] Indeed, this is exactly what a decision boundary is. In cases where the NPV rule is appropriate (i.e., there is no risk), benefits and costs have equal weight and $\Gamma=1$; thus there is no need to weigh benefits and costs differently. If $B_H\Gamma = B_X$, the manager should be indifferent between holding and exercising the management option, otherwise when $B_H\Gamma > B_X$, the decision to hold the option will be preferred. The reverse is also true.

The final step is to make a decision. A key difference between decision analysis and ROA is that in the latter case a decision can be made based on each pair of simulations, rather than having to make a decision based on the distribution of outcomes. Conducting multiple paired ROA simulations allows an analyst to look at a distribution of decisions. Results from these simulations can be plotted in a decision box with a mean decision boundary and percentile boundaries (Figure 9). However, each decision boundary corresponds to a specific estimate of benefits (actually their associated drift and volatility). It is informative to know what proportion of estimates fall between the boundaries created by the most extreme decision bounds, what proportion full above and to the left, and what proportion fall below and to the right. This gives the analyst the ability to examine a distribution of decisions, and thereby take account of the uncertainty associated with the decision boundary and the PA as a whole.

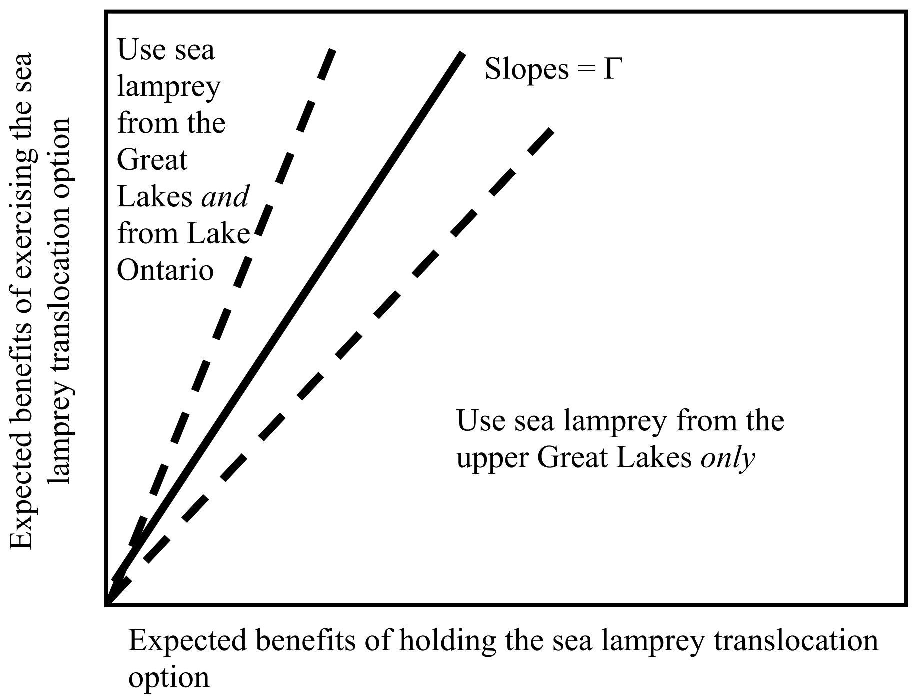

Figure 9. The decision box illustrates how multiple decision boundaries could be found from multiple simulations. The solid boundary represents the mean value of the precautionary multiplier Γ, while the dashed lines represent extreme boundaries occurring during the simulations.

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[12] In other words, the expected difference between the net benefits associated with exercising and holding the option should be maximized by choosing Γ so that the expected net gains, minus the cost of risk (taken from the volatility terms), is set equal to the discount rate (which represents the opportunity cost of forgoing returns that could be gained by exercising the option today). Thus Γ can be thought of as a weighting term (see Appendix 9.1). Also note that the only parameter that does not come from the simulation directly is the discount rate.

Sea lamprey translocation as a 'Real Option'
Employing the ROA approach, we rephrase the management question of sea lamprey translocation to say that the Great Lakes fishery managers have the right, but not the obligation, to begin using sea lamprey from Lake Ontario as part of the St. Marys SMRT program.[13] The manager must decide to either hold or exercise that option. Exercising the option means that the manager chooses to go ahead with the sea lamprey translocation and accept the risk of a potentially irreversible event – for example, the translocation and establishment of a new pathogen in the Upper Great Lakes. Holding the option means that the manager delays initiating the translocation of sea lamprey as part of SMRT until some future time. In the latter case the manager potentially accepts lower levels of sea lamprey suppression and a risk of a lower level of fisheries benefits. At a future time the value of option is reassessed and the manager may continue to hold the option or exercise the option (i.e., translocate sea lamprey) at that time.

We have discussed multiple approaches to evaluating fish translocation decisions: the NPV approach, the minimum safe standard, the precautionary principle, decision analysis, and ROA. The real options approach effectively integrates the minimum safe standard approach with decision analysis; that is, decision analysis is used to identify sources of uncertainty and pertinent research, and the real options methodology is used calculate a PA that is then applied in a similar fashion to the PA in the minimum safe standard framework.

Based on our review of the literature, we recommend ROA as the most suitable framework for evaluation of sterile male sea lamprey transfer decisions, and decision analysis for identifying future research needs. The next section of the report considers how such an analysis might be conducted.

Necessary steps for conducting a real options analysis of SMRT decisions

We advocate the application of ROA early in the model integration process. Use of ROA establishes a precedent for making decisions based on a quantitative evaluation that links precaution with risk. It is important to introduce managers to this approach as soon as possible, because we expect the uncertainty in the systems models to be large. Second, applying decision analysis to the preliminary models will help direct future research.

Steps 1 & 2: State objectives and define the option
We assume that *i)* the GLFC's goal is to maximize stakeholder surplus and *ii)* consensus has been reached about how to weigh the benefits for the various stakeholders (currently this is implemented through fish community objectives, but if objectives appear to conflict it will be necessary to focus on the larger goal). Many authors have discussed the need to understand the fisheries management system from 'control' to 'outcome', but the decision metric has not always been consistent (Bence *et al.* 2003; Lupi *et al.* 2003). To weigh costs and benefits, values must be in the same currency. To our knowledge no modeling effort has yet attempted to carry investments in sea lamprey control through to use and non-use fishery-related benefits.

We define the option as the right, but not the obligation, to translocate sea lamprey from Lake Ontario into the St. Marys River for the SMRT program.

Step 3: Construct an integrated model of 'the system'
Extensive research and modeling has been undertaken in an attempt to understand sea lamprey biology and control (see the *Journal of Great Lakes Research*, Vol. 29, Supplement 1 for reviews). The

[13] Note that Lake Ontario sea lamprey translocations began in 2003, and approximately 4,000 sea lamprey have been transolcated since. However, the approach we recommend here has merit for two reasons:

1. It is possible that no significant pathogen transfer has occurred, in which case there is still the opportunity to conduct a useful analysis, even though ideally it would have been conducted at the start of the program.
2. The emergence of VHSv has raised new issues that may make the timing opportune for a new approach to decision making about lamprey translocation.

integration of these models, while not easy, is imperative since ecological-economic systems often have emergent properties that are not readily recognized at the subsystem level (Mitsch and Day 2004).

Models of sea lamprey control and population dynamics, fish community dynamics, and fishery-related economics have already been constructed for the Great Lakes. These models include many assumptions about parameter values and functional relationships that are far from certain, but decision-makers do not have the luxury of waiting for improved models and more data. Adding model complexity may only be important if a decision 'threshold' is in the region of decisions being considered. We recommend developing an integrated model based on the key relationships illustrated in Figure 10 and presented in the works cited below.

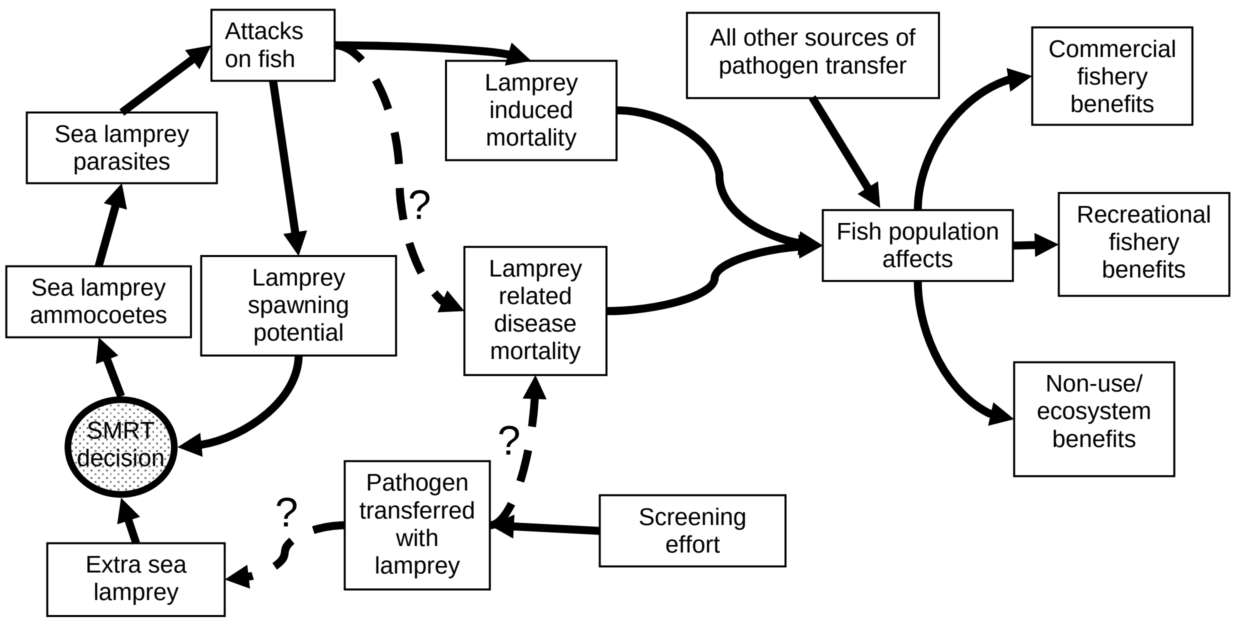

Figure 10. A conceptual model of the system; an integrative model of this type is the necessary foundation for subsequent real options analysis.

Sub-model 1: Linking SMRT to sea lamprey recruitment
It has been estimated that for spawner reduction methods to be effective in the St. Marys River, the effective spawner population size must be reduced by approximately 90% (Schleen *et al.* 2003). This is achieved in the St. Marys River both by trapping females and by releasing sterile males. This component of this system is illustrated on the left side of Fig. 10 by the boxes 'Extra sea lamprey', 'Sea lamprey ammocoetes', and 'Sea lamprey parasites'; the circle corresponds to the 'SMRT decision'.

Haeseker's (2001) model allows manipulation of the ratio of sterile to fertile males in the St. Marys River, and simulates the subsequent effects on the parasitic sea lamprey population in Lake Huron. Haeseker's (2001) model, which evolved from earlier efforts by Schleen *et al.* (2003), does not at present explicitly consider transfer of male sea lamprey from outside the basin - however the model easily could be adapted for that purpose.

Sub-model 2: Linking sea lamprey abundance to host fish population dynamics
Bence and his students have addressed the effects of changes in parasitic sea lamprey abundance on rates of attack on host fish, and consequent sea lamprey-induced mortality (Bence *et al.* 2003, Rutter 2004, Szalai *et al.* 2005). Using sea lamprey parameters developed by Rutter (2004), Szalai *et al.* (2005) developed short-term projection models for Lakes Huron and Michigan to project the effect of changes in

lake trout stocking and parasitic sea lamprey abundance on the population dynamics of lake trout and other host species. A key uncertainty within these models is the lethality of sea lamprey attacks on lake trout (i.e., what proportion of hosts die as a direct or indirect consequence of a sea lamprey attack?). Bence currently has a proposal before the GLFC to estimate directly sea lamprey mortality using statistical catch-at-age methods for Lakes Huron and Michigan. Successful results from this research could reduce this uncertainty. Other ongoing work by Bence to model Lake Huron fish communities could also contribute to future iterations of the model.

Sub-model 3: Linking fish population dynamics to stakeholder benefits
Less research has focused on how the state of the fish community translates into stakeholder benefits, particularly in economic terms. Traditionally, managers have focused on meeting fish community objectives established by the individual Lake Committees (G. Christie, GLFC, pers. comm.). However, to assess tradeoffs between management costs (i.e., sea lamprey control expenditures and disease risks) and benefits (use and non-use values), the units of measure must be in a common currency. Lupi *et al.* (2003) and Hoehn *et al.* (1996) conducted research estimating the benefits associated with varying catch rates in Great Lakes recreational fisheries. However, the importance of catch rates in angler decisions is often underestimated (Morey and Waldman 1998). Initially we could assume non-use and commercial benefits are correlated with recreational benefits (an assumption likely violated in reality), and use the marginal per fish value (Johnston *et al.* 2006) as an estimate of benefits. Alternatively, the relationship between catch and benefits could be modeled using Hoehn's *et al.* (1996) model of recreational demand for fishing in Michigan.

Commercial fisheries for species affected by sea lamprey are fairly small in Lake Huron, but data on landed values for the Lake Huron commercial catches could be added to a model of economic benefits. However, to date no work has attempted to quantify the ecosystem service or non-use benefits associated with the Great Lakes fish community; clearly, such work would assist in fisheries decision-making. Such data could be collected through survey research whereby anglers and non-anglers would be asked to trade off non-use fishery benefits against use (catch) benefits. For example, *how many native species are people willing to forego to achieve an increase in chinook salmon catch rates?* Such work will be important in determining tradeoffs between restoring native fish communities and supporting recreational salmonid fisheries. Such tradeoffs may well affect sea lamprey control and SMRT decisions.

Sub-model 4: Pathogen dynamics and invasion
Most of what is known about the dynamics of infectious diseases in Great Lakes fish populations comes from hatcheries or fish production facilities (Stephen and Thorburn 2002). Knowledge of fish-pathogen dynamics in the Great Lakes is extremely limited, despite evidence of the importance of diseases such as bacterial kidney disease for salmonid dynamics in Lake Michigan (Holey *et al.*1998, Benjamin and Bence 2003). There is little experience with disease outbreaks in the Great Lakes, making it difficult to model the potential extent of the impacts of an introduced virulent pathogen. Models of host-pathogen interactions have been used to improve and organize knowledge of host-pathogen dynamics in a small number of wild fish populations (Murray *et al.* 2001).

Nevertheless, lack of data on disease transmission data is not a barrier to exploratory modeling to investigate system dynamics (Caley and Hone 2004). Indeed, Tsao and Jones (2005) have begun developing models of fish-pathogen relationships in the Great Lakes focusing on *Renibacterium salmoninarum* (the agent of bacterial kidney disease) in Lake Michigan. Our ability to place bounds on pathogen or disease introduction events will improve as such models enable us to better understand interactions between pathogens and wild fish populations.

An additional source of uncertainty is the rate at which pathogens invade the Great Lakes and/or move between lakes. This uncertainty is indicated by the box labeled 'all other sources of pathogen transfer' in Figure 10. For the purpose of sea lamprey management, an appropriate baseline would be the rate at which pathogens move into the upper Great Lakes from all sources other than sea lamprey translocation. The invasive species literature could help calibrate this portion of the model. Recently, modeling efforts have begun to identify the probability of organism introduction to the Great Lakes via ballast water (Wonham *et al.* 2005) and organism translocation around the Great Lakes via recreational boat movement (Leung *et al.* 2006). This research may provide techniques for estimating pathogen transfer probabilities. As a first approximation, it may be assumed that the probability of a pathogen transfer may be proportional to the probability of organism transfer. An additional area of related research currently lacking is the rate at which natural fish movements can spread pathogens.

Sub-model 5: Screening effort
Great Lakes managers are hoping to reduce the risk of an adverse disease event by screening a subsample of sea lamprey prior to transferring the main translocation group (referred to as a 'batch'). Finding the optimal level of screening effort while simultaneously determining whether the optimal decision is to hold or exercise the translocation option is a complex problem and requires that the screening program be explicitly modeled within the overall system model. Alternatively, the efficacy of different levels of screening can be evaluated through a sensitivity analysis; we illustrate this in Section 5 of this report.

To incorporate the effect of screening protocols into the integrated model, other probabilities also need to be assessed. Specifically, we also need to know the probability of pathogen establishment and of damaging effects on host populations given that a translocation occurs. There are often little or no data on these probabilities, particularly for aquatic systems; however Williamson (1996) does offer a 'rule of tens' for biological invasions in general. That is, 10 percent of biological invaders will become established, and 10 percent of those will become pests. Such rules can aid in building the first round models. The important question is, "might alternative levels of screening alter the decision to transfer Lake Ontario sea lamprey to the St. Marys River as part of the SMRT program?"

Steps 4 & 5: Use the first-generation integrated model to estimate the drift and volatility of benefits, the key areas of uncertainty, and the precautionary multiplier Γ
The real options approach will help guide decision making based on what we know today and will also guide future research. By coupling existing models, we can create a preliminary integrated model to estimate how sea lamprey control under different screening strategies might affect benefits over time, conditional on existing information. An integrated model can be used to develop paired computer simulations (i.e., exercising and holding the translocation option). From these simulations, using the procedures outlined in Section 3.3 and Appendix 9.1, it will be possible to estimate the drift (expectation of the change in benefits) and volatility (best estimate of risk) of benefits – all the necessary components to conduct ROA. Moreover, once the models are integrated, key areas of uncertainty as they relate to benefits can be identified. Figure 10 illustrates a conceptual model that would carry management decisions through to benefits. The integrated model will enable a sequence of forecasts such as: "adding additional sea lamprey from Lake Ontario is forecast to reduced parasitic sea lamprey by $x \pm y$%. This leads to a $u \pm v$% increase in lake trout abundance. Pathogen introduction and a mass mortality event are hypothesized to follow a Poisson distribution that would result in an expected z% reduction in the lake trout population," and this has w impact on the overall benefits received by stakeholders.

Step 6: Make a decision and/ or initiate research to reduce uncertainty
It is possible that the first stage of modeling will provide a definitive answer. It may be the case that the benefits of using Lake Ontario sea lamprey in the St. Marys River SMRT program swamp the risks of any disease event. This would be the case if the benefits of translocation where always larger then the benefits of forgoing the translocation multiplied by Γ, even when Γ is large. Conversely, the analysis may conclude that SMRT translocations do not provide substantial benefits, even with low risk. This would be the case if Γ was relatively small (close to one) and the expected benefits of translocation do not overcome the benefits of forgoing translocation multiplied by Γ. A third, and likely, possibility is that Γ will be large and the benefits do not exceed the costs multiplied by Γ. In this case it would be optimal to hold the option, with this decision being driven by a high value of Γ (as opposed to a low estimate of the

translocation benefits). Therefore, a second iteration of modeling will be appropriate, after some key uncertainties have been reduced.

The real options approach is naturally iterative. Conducting a ROA answers the question, 'Do we exercise the option (i.e., enact the translocation of sterilized male sea lamprey from Lake Ontario to the St. Marys River), or do we instead hold the option (i.e., delay the translocation of Ontario sea lamprey until uncertainty is reduced)?' If initial models fit poorly or are data-limited, and the benefits of exercising the option are modest, then an ROA will likely conclude that it is optimal to hold the option and delay the enactment of the program. Such a result allows time for further study to help reduce our uncertainty.

In some cases uncertainty may be reduced through empirical work (e.g., surveys of potential pathogens, or of stakeholders to assess non-use values), while in other cases refinements to the initial models may be called for. For example, using marginal per-fish values (cf. Johnston *et al.* 2006) would ignore the influence of catch rates on the marginal value of fishing. The model could be improved by adapting (and possible updating) the Hoehn *et al.* (1996) model of benefits from recreational fishing. Updating the Haeseker (2001) model of sea lamprey recruitment dynamics or including Bence's expected estimates of sea lamprey induced mortality are other examples of improvements that should reduce Γ. If the decision to hold the option is still driven by a large Γ, then a new decision analysis should be conducted to help identify a new set of research needs. This iterative process will continue under two conditions *i*) the condition that the option is held; and *ii*) the decision to hold the option is driven by a large value of Γ. The duration of this and any subsequent steps that might be justified by the analysis will depend on the tradeoff between the urgency of the decisions and the time it takes to acquire critical data. The spacing of iterations and the time needed to implement them will be determined by the needs of the decision makers. However, there is a tradeoff: shorter iterations will carry more uncertainty and the informational benefits of performing a new iteration may not outweigh the costs.

It is not possible to tell how many iterations of the analysis will be needed, but clearly it is not an indefinite process. If Γ remains large and upon future iterations fails to decline, managers may choose to hold the option indefinitely. That is, they would forgo translocations, shelve the option, and put off re-evaluation for a longer time period (or indefinitely). Conversely, if managers exercise the option, there will be no need to continue reevaluating the option unless it is believed that the system has changed in an unexpected way.

Anticipated outcome of the ROA

A key aspect of this iterative process will be to communicate clearly the findings to Great Lakes fishery researchers and managers. Certainly the data collection, analysis, and modeling that comprise this process will yield wider benefits than just for decisions about moving sea lamprey from Lake Ontario to the St. Marys River. The findings are likely to provide valuable methodological guidance for other fish movement issues in the Great Lakes, and the modeling will provide insights for other management issues, such as integrated control of sea lamprey in the St. Marys River and elsewhere.

The real options approach phrases the question about irreversible decisions differently than other techniques: "Is there enough information to proceed with an irreversible decision or should we delay until more information is gained?" Of course sometimes the expected benefits of the irreversible program will be much less than the benefits of not conducting the irreversible program at all. In such cases a manager may simply choose to discontinue the evaluation, thereby effectively scrapping the option. Even if the uncertainty is small and the value of the option is small ($\Gamma \approx 1$) it still may not be optimal to make an irreversible decision. Conversely, even if $\Gamma >> 1$, the expected benefits from making the irreversible decision may swamp the costs and value of holding the option. This implies that uncertainty does not have to be eliminated before an irreversible decision can be made.

A real options approach is predicated on learning and the consequential reduction of uncertainty over time. The value of the option arises from the opportunity to gain knowledge while the option is held. If nothing new can be learned, then nothing is gained by delaying. In this case, a regular disease surveillance program is imperative to quantifying and ultimately reducing a key source of uncertainty. In Section 5, we consider the specific issue of pathogen screening within the broader context of an ROA framework for SMRT decision-making.

Timeline for an ROA on SMRT sea lamprey translocations

We estimate that the first iteration of a model useful for conducting a ROA would take approximately six months if an analyst could be dedicated to this process. This stage would involve the use of available models mainly calibrated based on older data. A model interface would also be developed during this time. This stage would demonstrate the ROA processes, and provide a first estimate of Γ.

If large values of Γ are driving the decision, and if research gains are anticipated, a second iteration may be desirable. The second iteration should reduce uncertainty so that large values of Γ are not overwhelming other costs. This second iteration might involve new models and revised parameters based on new data. Some of this work could begin immediately following the completion of the first iteration. A minimum 18 month gap between completion of the first iteration and second iteration may be appropriate, depending on research developments.

Analysis of the present SMRT pathogen screening strategy

The role of screening

Disease surveillance provides information about the host-pathogen system, but at a cost. In the case of sea lamprey screening, the diagnostic tests are applied post-mortem, so screening decreases the number of sea lamprey that can be transferred for a given capture-and-transfer effort. Moreover, as many as 25% of the sea lamprey that are held for translocation while screening is being conducted (on a separate subsample) may die (G. Christie, GLFC, pers. com.). These deaths may be due to containment stress or that sea lamprey are semelparous, and the held fish have already entered the spawning phase of their life. More generally, the costs of screening include a reduction in resources that could potentially be better used elsewhere and hence, decrease the efficacy of the entire program.

Sea lamprey screening is of little value unless there is pathogen distribution and prevalence information from the donor and recipient lakes (see Figure 11) (Leighton 2002). Information is needed about the pathogen status of the donor lake fish community so that the diagnostic testing can be focused on the pathogens of greatest concern. It would be hugely costly to screen for every potential pathogen. Similarly, information is needed about the pathogen status of the recipient lake, to know which pathogens identified by screening would be 'new'. Pathogens that are present already and perhaps widespread in the recipient lake would not merit suspension of translocation efforts. Finally, for perspective on the relative risk of pathogen introduction via sea lamprey translocation, one needs to consider pathogen introduction and spread due to other routes.

An effective sea lamprey surveillance program needs to address four objectives:

1. Identify potentially harmful pathogens in donor lakes;
2. Assess the likelihood that any such pathogens are already present in recipient lakes;
3. Determine the relative pathogen dispersal potential of various pathways including natural dispersal and human facilitated translocation;
4. Assess the likelihood that translocated sea lamprey will introduce new and potentially harmful pathogens to recipient lakes that are unlikely to be dispersed through other pathways.[14]

[14] With regard to Objective 4, it could be argued that transfers of sea lamprey infected with pathogens should sometimes be blocked even if those pathogens are already known from the recipient lake, as increasing the prevalence of an existing pathogen might push it over a threshold for triggering epidemic disease. We do not address this possibility further, in part because it seems unlikely that the biomass of lamprey being translocated annually could have a measurable effect on the prevalence of any pre-existing pathogen that is already common enough to have been detected in the recipient lake, given the limited surveillance that presently occurs.

Objectives 1, 2, and 3 are beyond the scope of this report. Before expanding on Objective 4, however, it is worth reflecting on how pathogens may be detected outside of active surveillance. Only a well-designed and implemented active surveillance program will provide the data needed to enable a careful analysis of the benefit-costs of translocation. Yet, the public, rather than agency surveillance efforts, often first notice diseased individuals in wild populations. For example, the first confirmed detection of *Heterosporis sp*. in Lake Ontario came from an angler who submitted two yellow perch from Prince Edward Bay that showed signs of disease (Hoyle and Stewart 2002). The public has many more eyes than any agency-based surveillance program. Thus, fish managers may want to consider creative ways to employ the public in a dependable passive surveillance system to complement an active surveillance program. For example, the Michigan Department of Natural Resources (MDNR) relies on voluntary submission of deer heads during the hunting season to survey for the bacterium that causes bovine tuberculosis in white-tailed deer, which has greatly augmented the MDNR's ability to detect new areas of infection.

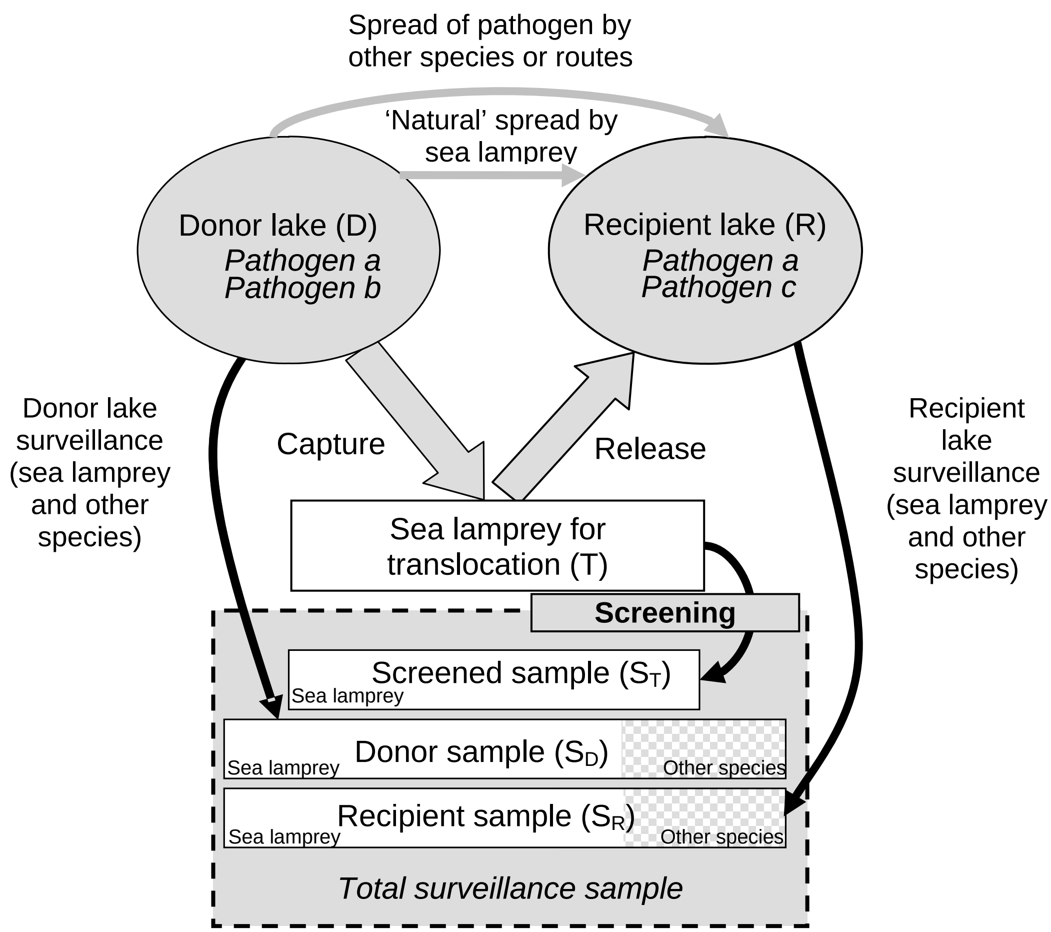

Figure 11. Pathogen dispersal routes and pathogen screening program characteristics to considered when assessing the benefits and costs of pathogen SMRT sea lamprey screening. Grey lines represent between-lake movement; black lines represent sampling for surveillance. In this model, screening provides three kinds of information to managers: *i)* surveillance of the entire fish community in the donor lake to alert managers to the presence of pathogens of concern; *ii)* surveillance of the entire fish community in the recipient lake to identify donor-lake pathogens already present; and *iii)* surveillance of a sub-sample of translocated sea lamprey to reduce the risk of introducing pathogens.

We now focus on Objective 4 – the lamprey screening program. In designing a pathogen/disease screening program, two key attributes must be addressed: how *hard* to look and how *long* to look. The remainder of this section considers these two components in turn. First, we examine the issue of how hard to look (section 5.2). Then we explore techniques for determining how long to continue surveillance (section 5.3). Throughout these discussions, which are based largely on probabilistic models, we emphasize the relationship between model assumptions and objectives.

Managers must understand how the prevalence of a pathogen affects their broader objectives – simply minimizing disease prevalence is not sufficient for aiding in resource allocation decisions. It is also important to remember that resources spent on *looking harder* or *looking longer* might be better used elsewhere to achieve broader fisheries goals. Moreover, verifying the absences of an organism is almost impossible and almost infinitely costly (Regan *et al.* 2006). Throughout this section, the reader needs to ponder, 'what is an acceptable level of pathogen prevalence?' Stephen and Thorburn (2002) point out that fish health must be defined beyond the absence of disease; parasites are a part of functioning ecosystems; and health definitions for population management must be 'problem-based.' Clearly, the models discussed in the preceding section are necessary to answer this question, which highlights the importance of integrating models of the system.

How hard to look for unwanted pathogens

Verifying the absence of a pathogen is all but impossible, and the harder one looks the more likely one is to find a pathogen. The important question is how many resources to allocate to searching for pathogens. A batch of sea lamprey is a sample drawn from the population of fish in the donor lake for the purpose of translocation. A subsample of sea lamprey drawn from the batch is screened for pathogens. For a screening program to work, the subsample of sea lamprey must be a representative (i.e., random) sample of the transfer batch. Formally, we would say that the probability of any given sea lamprey hosting a pathogen would be independent of any other sea lamprey hosting a pathogen, and that the probability that any given sea lamprey would be a host is the same regardless of whether the sea lamprey came from the subsample, the batch, or the larger population found in the donor lake.

If the prevalence is high enough to detect one or more infected sea lamprey in the subsample, then clearly there are likely to be additional infected fish in the translocation batch. In such a case, the outcome is straightforward: do not translocate the batch.

If the pathogen is not detected in the subsample, however, we only can conclude that the prevalence of the pathogen in the larger transfer batch is likely to be below some level, at some stated level of confidence. For example, we might conclude that we are 95% certain that the prevalence of disease in the transfer batch is below, 5%.

Let us now assume that the lack of any detectable pathogen in the screened sample means that the field staff will be given the go-ahead to translocate the batch. As the number of sea lamprey in the transfer batch increases, so does the probability that an undetected pathogen will indeed be present in that translocation batch. Thus, the statistic of interest is the probability that a pathogen could be present among the sea lamprey to be released, given that the pathogen was not detected in the subsample. This probability of transferring a pathogen given screening is calculated as the joint probability of failing to detect the pathogen during screening and the probability that the transfer batch does in fact host the pathogen (Equation 5 and Figure 12):

(5) Pr(transferring a pathogen) =[1-Pr(of detection in the screening process)] * Pr(of presence in the sea lamprey transfer batch)

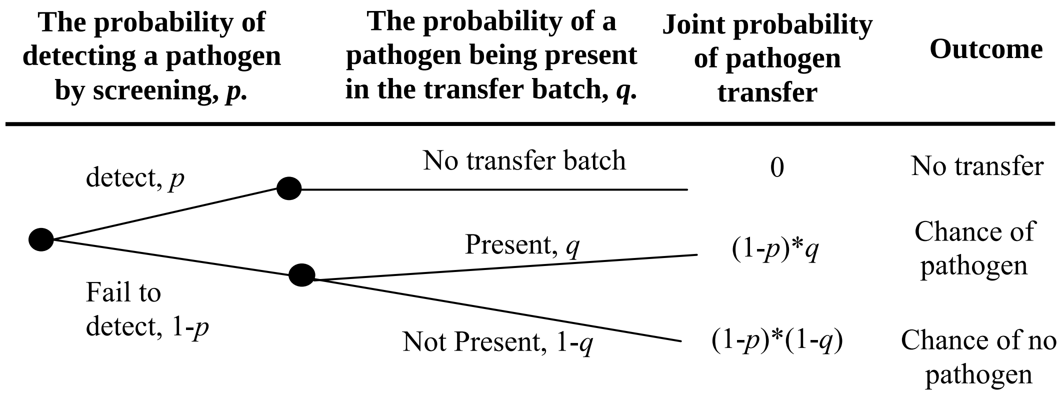

Figure 12. The probability of transferring a pathogen given screening. If a pathogen is discovered upon screening, there is no translocation. But, if a pathogen is not discovered upon screening, it still may be present in the batch to be transferred. The probability of transferring a pathogen given screening is equal to the joint probabilities of (1-p)*q.

The probability of failing to detect a pathogen, (1-p)
For a given level of pathogen prevalence, the probability that screening sea lamprey will detect the presence of an unwelcome pathogen is straightforward to calculate - requiring information only on *i*) test sensitivity, *ii*) test specificity, and *iii*) the number of individual sea lamprey screened. Because we often do not know the prevalence of a pathogen for which we are screening, we set the target probability of pathogen detection for a previously decided maximum allowable prevalence level. For example, the GLFHC has set the desired probability of pathogen detection to 0.95 for a maximum allowable pathogen prevalence level of 5%. Given these parameters, one can calculate the number of sea lamprey that must be screened to be able to detect *at least* one infected sea lamprey. Consequently, the probability of *not* detecting the pathogen is simultaneously set; in the example above, the probability of *not* detecting a pathogen is set at 0.05 (1-p in Figure 12).

If we assume 100% accuracy of the screening instrument, Green and Young's (1993) equation for rare organism surveys can be applied to the screening program:[15]

$$n = -\frac{1}{m}\ln(1-x) \tag{6}$$

In equation 6, n is the necessary sample size, m is the maximum acceptable prevalence, and x is the desired level of confidence. Figure 13 relates the number of sea lamprey that need to be in the screened subsample to achieve 95% confidence for a given maximum acceptable prevalence. As the maximum acceptance prevalence level decreases, the number of sea lamprey needed to be tested to achieve 95% confidence of detection increases at a rapidly increasing rate; going to infinity as prevalence goes to zero (note that the y-axis in Figure 13 is on a log scale).

[15] While it is unlikely that the screening instrument is 100% accurate, this simplifies the exposition; it is straightforward to modify the calculations to account for the probability that the test is accurate.

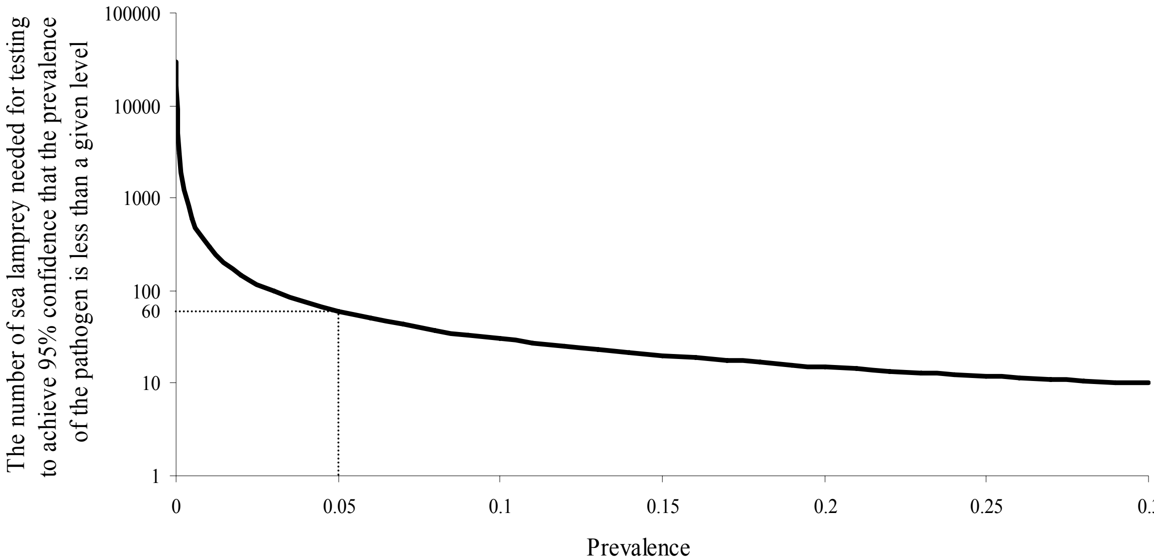

Figure 13. The number of sea lamprey that need to be tested to achieve 95% confidence that a pathogen is absent from the transfer batch at a given prevalence level. The calculation for 5% prevalence is identified with a dotted line. Note that the y-axis is on a log scale.

Equation 6 can be rewritten to provide the probability of detecting a pathogen in a sample of a given size from a population with a known (or assumed) prevalence (Eq. 7). To calculate the number of sea lamprey that need to be tested in order to achieve a certain probability that at least one infected sea lamprey is detected, simply let the maximum acceptable prevalence level be the assumed prevalence.

(7) $$x = 1 - \exp(-mn)$$

The probability that the pathogen is present in the batch of sea lamprey to be translocated, q

From Equation 7, we can calculate the probability that a pathogen is present in the batch of sea lamprey to be translocated (q in Figure 12), given additional information regarding how many untested sea lamprey are awaiting release. Table 2 contrasts four cases, where the maximum acceptable prevalence of a given pathogen in the fish community as a whole is 0.1%, 1%, 5%, and 10%. For all prevalence levels, as the number of fish translocated increases, the probability that there is at least one infected individual in the batch also increases. For example, when 200 sea lamprey are to be translocated, the probability that the batch includes at least one infected sea lamprey is 0.18, 0.86, 1.00 and 1.00 when the true prevalence is 0.1%, 1%, 5%, and 10%, respectively. Table 2 may also be read as the necessary number of sea lamprey to screen to detect a pathogen at a certain prevalence level with a given confidence level.

Table 2. The probability that a given pathogen would be present in a sample of a given size (or detected in a subsample with a perfect screening test), for different prevalence levels of the pathogen in the source lake fish community.

Pathogen prevalence in the fish community	Number of sea lamprey in the sample					
	30	**60**	**200**	**300**	**500**	**1000**
0.001	0.03	0.06	0.18	0.26	0.39	0.63
0.01	0.26	0.45	0.86	0.95	0.99	1.00
0.05	0.78	0.95	1.00	1.00	1.00	1.00
0.10	0.95	1.00	1.00	1.00	1.00	1.00

When the prevalence of the unwanted pathogen is very high, the situation is straightforward: infected sea lamprey will show up during screening and the translocation of the batch will be halted. Similarly, when the prevalence is near zero, the situation is again straightforward: the pathogen is unlikely to be present in either the screened sample or the translocation batch, and so it is safe for the transfer to proceed. However, as shown in Table 2, at a moderately low prevalence the situation is more challenging because the pathogen may not be detected in the smaller subsample, but is likely to be present in the much larger batch (Bergstedt and Twohey 2005).

The joint probability of releasing an infected sea lamprey given that the pathogen was not detected in the initial screening program: a worked example

In May 2004, just over 600 sea lamprey were captured in Lake Ontario for transfer as part of the SMRT program (G. Christie, GLFC, pers. comm.). Sixty-one were sent to the Aquatic Animal Health Laboratory and examined for disease signs and the presence of selected pathogens. Two individuals tested positive for *Renibacterium salmoninarum*, the causative agent of bacterial kidney disease, and all tested negative for *Heterosporosis sp*. *R. salmoninarum* was not considered a pathogen of concern because the strain isolated “resembles those [previously] isolated from Lake Michigan” (M. Faisal, unpubl.). [16]

The SMRT field staff followed the recommended screening process for SMRT sea lamprey: 60 individual sea lamprey from the batch were screened, affording a 95% probability of detecting one or more infected sea lamprey, if the prevalence of disease in the screened subsample exceeded the 5% level considered ‘acceptable’ by the GLFHC (see Figure 13).

In Lake Ontario, if the prevalence of *Heterosporosis sp.* among sea lamprey in fact had been 5% (this is a purely hypothetical, for the sake of example), then testing 60 sea lamprey would provide a 5% chance that the pathogen was not present in the screening subsample *despite* being present in the source population. If the prevalence of *Heterosporosis sp.* was actually 10%, then testing 30 sea lamprey would be adequate to achieve the same low probability of failing to detect the pathogen. On the other hand, 300 sea lamprey must be sampled to achieve the same low probability if only 1% of the fish in the source population were infected. Finally, for a hypothetical prevalence of only 0.1% (1 infected fish per 1000 individuals), even after testing 1000 sea lamprey, one would only be 63% confident that the prevalence of pathogen was indeed less then 0.1% (see Table 2, first row, final column). These calculations clearly demonstrate that as the maximum allowable detection prevalence level decreases, the sample size required to detect an infected individual increases rapidly.

If 5% of the sea lamprey in Lake Ontario were infected with *Heterosporosis sp.*, then from Table (2) we can be 95% confident that at least one infected sea lamprey would appear in a subsample of 60 sea lamprey. Furthermore, if 5% of the sea lamprey in Lake Ontario were infected with *Heterosporosis sp.*,

[16] In other words, *R. salmoninarum* is an example of pathogen **a** in Fig. 11.

than from Table (2) we can be almost 100% confident that one infected sea lamprey will be in a batch of 200 sea lamprey (400 less than were actually transferred). We can use these results along with equation (5) to calculate the joint probability that a sea lamprey infected with *Heterosporosis sp*. will be transferred: (1-0.95)*1 = 0.05. Thus, there is a 5% chance of pathogen translocation.

We can apply the same procedure to the case where we assume 1% pathogen prevalence in the source population. In this case, we are 45% confident that an infected individual will show up in a sample of 60 sea lamprey, and 86% confident that there will be an infected individual in a batch of 200 (Table 2). Again, applying equation (5) we see: (1-0.45)*.86 = 0.47. In other words, there is a 47% chance that at least one infected sea lamprey will be transferred to the St. Marys River. Moreover, we can be almost certain that there would be at least one infected individual in the batch of 600 fish actually translocated during the SMRT program. This implies that there would have been a 55% chance that at least one infected individual was moved from Lake Ontario to the St. Marys River. To put these example in perspective, from 2003 to 2006 the number of sea lamprey moved from Lake Ontario via the SMRT program was 368, 600, 1,756, and 1,200 respectively (G. Christie, GLFC, pers. comm.).

Figure 14 illustrates how at very low prevalence levels the probability of transferring an infected sea lamprey is low as the pathogen is unlikely to be present in either the subsample or the transfer batch. As pathogen prevalence increases the probability of transferring an infected sea lamprey increases because there are fewer individuals in the screened subsample than in the batch. As the prevalence level continues to increase, the probability of detecting the pathogen in the subsample increases, and thus the probability of transferring an infected sea lamprey decreases. Compared to large subsamples, smaller subsamples will result in higher probabilities of translocating an infected sea lamprey over a wider range of infection prevalence levels, all else equal. However, increasing subsample size has less of an effect on decreasing the likelihood of a translocation as prevalence increases. If prevalence is high enough then smaller samples may be nearly as likely to detect the presences of the pathogen (Figure 15). Increasing the size of the subsample will have the largest effect at moderately low prevalence levels (Figure 15).

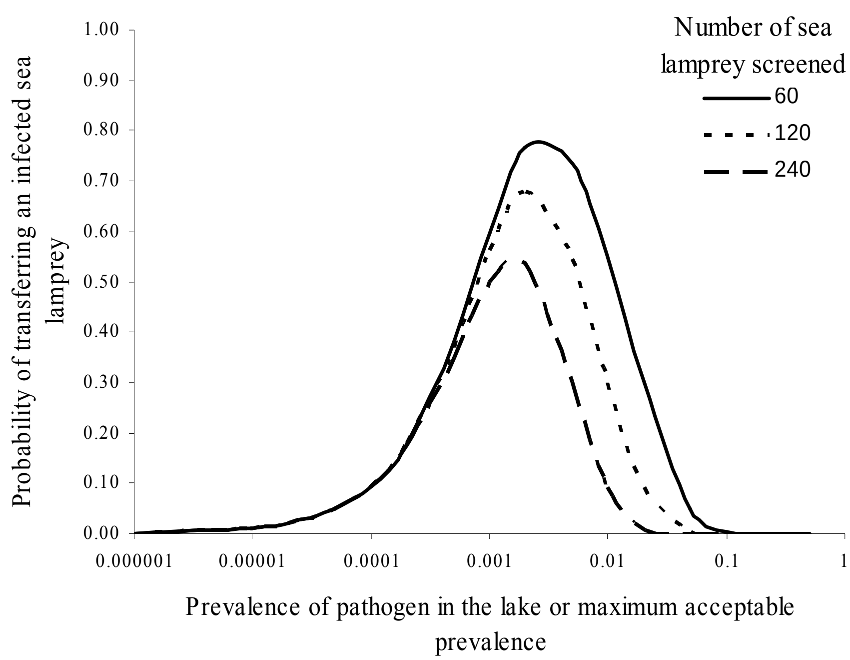

Figure 14. The probability that an infected sea lamprey will be transferred given different levels of source lake prevalence and screening effort, assuming 1,000 fish are translocated. Note that the x-axis is on a log scale.

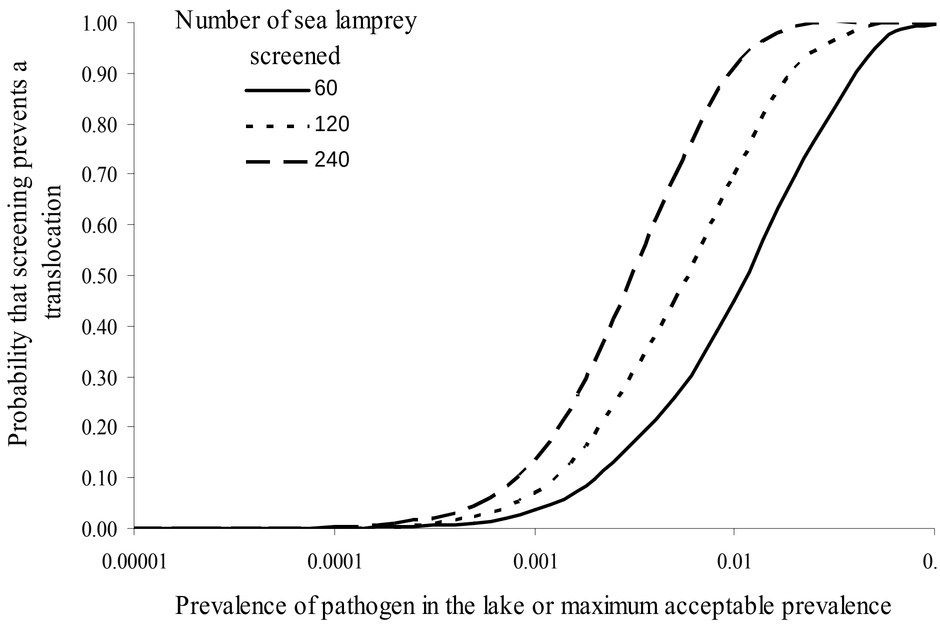

Figure 15. The probability that the screening program prevents the transfer of an infected sea lamprey at a given source lake pathogen prevalence with a given screening effort, assuming that 1,000 sea lamprey are transferred. Note that the x-axis is on a log scale.

The interaction between screening effort and the number of sea lamprey transferred to the St. Marys River given a source lake prevalence rate is illustrated in Figures16 (prevalence = 0.05) and 17 (prevalence = 0.01). The probability of transferring an infected sea lamprey decreases as the number of sea lamprey screened increases. The probability of transferring an infected sea lamprey also increases for a given number of sea lamprey screened as the number of sea lamprey transferred increases. As the maximum allowable pathogen prevalence decreases, the probability of transferring an infected sea lamprey is greater for a given number of sea lamprey screened and a given number of sea lamprey transferred.

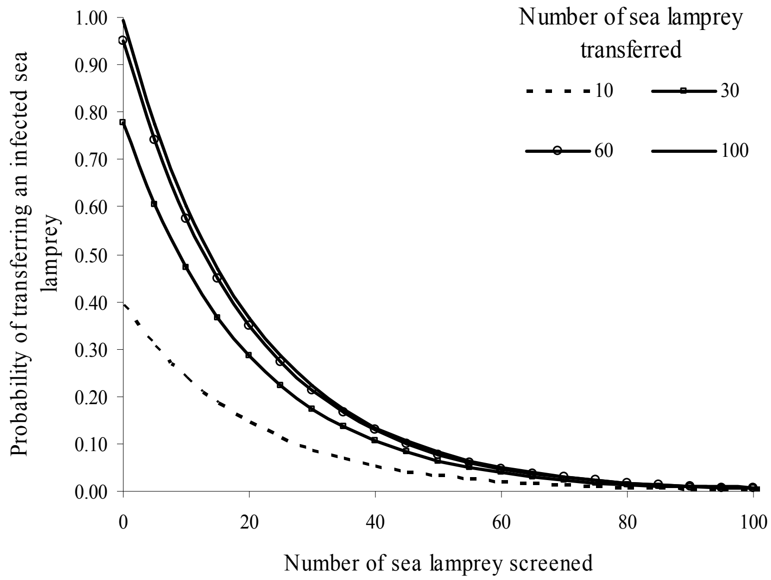

Figure 16. The probability that an infected sea lamprey is transferred given the number of sea lamprey transferred and screening effort assuming a 5% prevalence level.

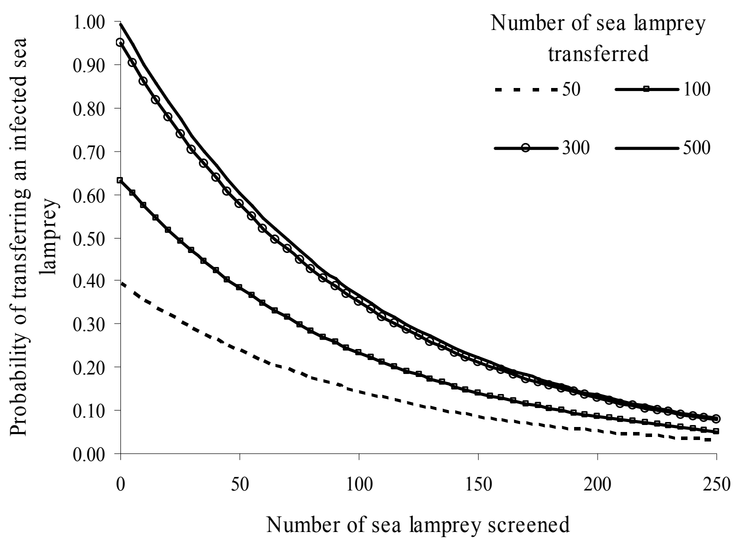

Figure 17. The probability that an infected sea lamprey is transferred given the number of sea lamprey transferred and screening effort assuming a 1% prevalence level (note that *x*-axis and number of sea lamprey transferred are not the same as in Figure 16).

From the above analyses, we conclude that transfer of an infected sea lamprey is most likely to occur at moderately low prevalence levels (see Fig. 14). This is because the probability of failing to detect infected sea lamprey through screening declines as pathogen prevalence increase, while the probability that an infected individual would be in a batch for translocation declines as prevalence falls. The probability that the screening program prevents a translocation event is the intersection of these probabilities. Sea lamprey screening is most likely to provide benefits when pathogen prevalence is relatively high, >5%, in which case small subsamples may be adequate (Figures 14 and 15). However, there are gains to be made by increasing subsample size. Screening also reduces the probability of a pathogen translocation event when the number of individuals screened represents a substantial fraction of the number being translocated (Figures 16 and 17).

It could be argued that only high-disease-prevalence batches of sea lamprey pose any major threat of triggering outbreaks in the recipient lake, since an individual sea lamprey is unlikely to shed enough pathogen (or survive long enough) for the pathogen to persist and establish in the recipient lake. Moreover, an individual sea lamprey that is shedding pathogen might be expected to infect others that it is being housed with during transport and screening, and thus may further increase the probability of pathogen detection. That argument is, however, contingent on the specific biology of each pathogen of concern (e.g., some pathogens may have carrier states in certain seasons and so would not be infectious while being held).

How long to continue looking for pathogens?

The other important question in designing a screening program is, how *long* to keep looking? If a pathogen is not found in successive years, and there is no other reason to believe that an introduction has taken place, then how long should the sea lamprey screening program persist? The GLFHC currently recommends that hatcheries test negative for pathogens for three consecutive years to be considered disease free, but no such rule has been developed for sea lamprey screening (G. Wright pers. com.). Regan *et al.* (2006) introduce a framework for evaluating search programs for invasive plants that we have adapted to this question. The length of time a screening program should persist given that no infected individuals are found should be based on three factors:

1. The expected cost of facilitating a disease translocation or introduction;
2. The cost of the screening program.
3. The probability of facilitating a disease translocation.

Regan *et al.* (2006) offer two techniques to determine the number of years that surveillance should continue once no infected individuals are found. The first involves solving an optimization problem, and the second is a ‘rule of thumb’ calculation. They state that their rule of thumb calculation performs well when compared to solving the optimization problem, although the rule of thumb calculation is slightly biased in a conservative direction (i.e., the rule of thumb calculation will recommend a longer surveillance period). We recommend this same rule of thumb as a way to obtain a first approximation for how long the sea lamprey screening program should continue:

$$y = \frac{\ln\left(\frac{-CS}{CE * \ln z}\right)}{\ln z} \tag{8}$$

where y is the number of consecutive years that screening should continue when no pathogen is being detected, CS is the cost of the screening program, CE is the cost of facilitating a pathogen translocation (Regan *et al.* (2006) refer to this as ‘escape’), and z is the probability that an undetected, infected sea lamprey is transferred, assuming the translocation of single infected sea lamprey results in a damaging disease outbreak.

Currently, the GLFC pays $30 per sea lamprey screened. This figure represents a conservative estimate of costs since it does not include field labor or transportation costs (G. Christie, GLFC, pers. comm.). Higher costs would shorten the length of time that screening should continue. The probability z was discussed at length in the previous section. The CE is unknown, since pathogen translocation via the SMRT program is only one component of the larger system, as sea lamprey translocations carry both benefits and costs (see Figures 10 and 11). In Figure 18, we illustrate how these three quantities interact to determine the number of years screening should persist if screening finds zero infected individuals in the subsamples and assuming that the translocation of a single infected individual does indeed cause an outbreak.

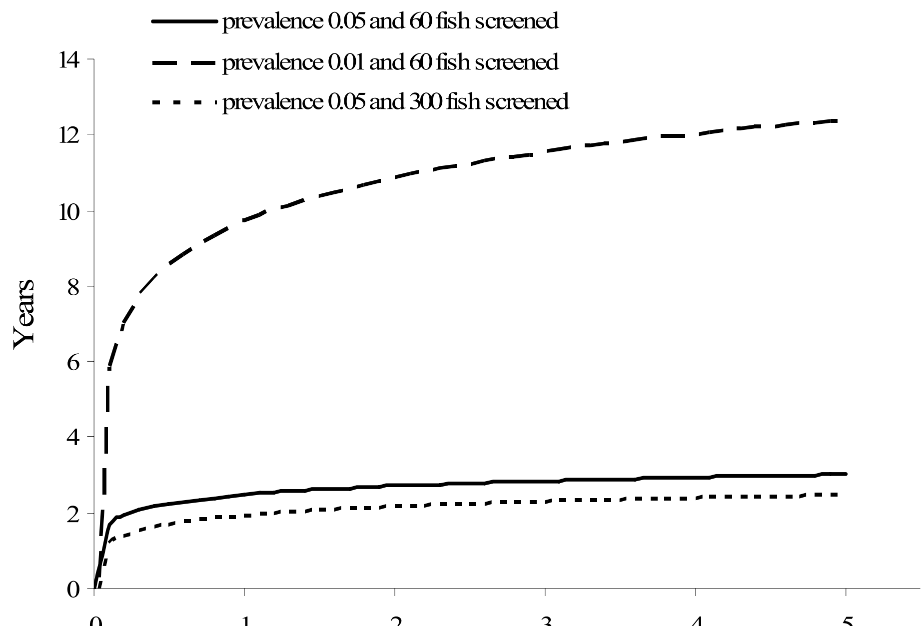

Figure 18. The effects of screening costs, the cost of a disease outbreak, and the probability of introduction on the years that a screening program should continue given that no infected individuals are found. The cost of the screening program equals $30 multiplied by the number of fish screened. The prevalence rate is the assumed background prevalence rate, therefore the probability that an infected fish is transferred, assuming 1,000 or more fish are translocated can be found using Table 2. We assume that a translocation is sufficient for a disease outbreak.

Figure 18 leads to four observations. First, the cost of a disease outbreak has a relatively small effect on the length the screening program should continue if zero infected individuals are found except when costs are relatively small. Second but more difficult to see, all lines cross the *x*-axis at a value greater than zero. This indicates that if the expected damages are small enough, screening should not take place. Third, from Table 2 we see that the dashed line and the dotted line cases have the same probability of pathogen translocation. However, more fish must be screened to achieve the low probability in the case of a source prevalence of 1% (dotted line), and the screening program should terminate slightly sooner, assuming no infected individuals are found. Finally, the cases indicated by the dashed and solid lines both test 60 sea lamprey. However, the lower source prevalence in the dashed line case (1%) increases the probability of transferring a pathogen (assuming > 1,000 sea lamprey are transferred) to 55% because screening is less likely to detect infected individuals. This implies that screening programs that provide lower confidence should persist longer.

These calculations are based on the assumption that a pathogen is not currently invading (i.e., increasing in prevalence) the sea lamprey population, but is being maintained at a steady level or declining. If it is believed that pathogen prevalence is more likely to be increasing in the sea lamprey population than decreasing, screening should persist, but if this is case overtime infected individuals should also begin to appear in the screening subsample. A key point made by Regan *et al.* (2006) is that the cost of the screening program matters. If the cost of the screening program exceeds the benefits from translocating sterilized male sea lamprey, then the translocation should be forgone. On the other hand, the screening program is costly and the translocation of sterilized male sea lamprey provided benefits (all else equal). Therefore, the screening program should be run efficiently. That is, once acceptable detection probabilities and prevalence levels are established, the screening should be discontinued after a period of time, if negligible new information is being gained.

DISCUSSION

General conclusions

The risk of introducing a pathogen through sea lamprey translocations from Lake Ontario via the SMRT program cannot be properly assessed without also considering the benefits and costs of the translocation as a whole. Moreover, the uncertainty associated with the probability of transferring a pathogen is not the only source of uncertainty. The use of real options analysis (ROA), extends traditional decision analysis and can help guide fish translocation decisions in the face of multiple sources of uncertainty. ROA analysis is a precautionary approach that couples the level of precaution merited with the degree of risk faced by managers. That is, it provides precaution against being overly cautious and also against being rash. ROA helps managers determine how much certainty is necessary to make a decision. As more data become available and uncertainty is resolved, managers face less risk, and arguments in favor of precaution are reduced. Thus there is a 'learning cycle' (Figure 4). There is a strong link between this approach and the concept of adaptive management *sensu* Walters (1986).

The risk of introducing a new disease is dependent on the likelihood that disease is not already present in the recipient lake to which the sea lamprey are being transferred. Baseline data on the pathogen status of each lake will reduce the current uncertainty; a comprehensive pathogen testing program therefore has value beyond its biosecurity function, because it provides improved disease prevalence estimates for the lakes involved in the translocation program.

We suggest that the current screening program may provide a false sense of security, since transfers of infected sea lamprey are likely to occur if pathogens are present. Nevertheless, it is also unclear whether occasional transfers of pathogens represent a significant hazard. Presently there are inadequate data to determine whether the probability of a disease outbreak and its impacts on society. Indeed, managers must weigh the risk of occasional pathogen translocations via the SMRT program with the risk of failing to adequately suppress sea lamprey in the St. Marys River. We presently have no way to estimate the chances that pathogens will invade the Upper Great Lakes through some channel other than sea lamprey transfers (Figures 10 and 11), which obviously determines the extent to which sea lamprey translocation represents a significant additional risk. Thus, an integrated modeling approach is needed to assess the benefits and costs of the SMRT program in the larger context of Great Lakes fisheries management.

Recommendations

- A necessary first step towards a real options analysis (ROA)- or any similar integrative, bioeconomic analysis - of the sterile male sea lamprey release program is to begin integrating current models of Great Lakes fishery management;
- A preliminary ROA should then be conducted on the sterile male sea lamprey release system, with particular emphasis on inclusion and examination of the screening component of the program;
- New field data will be required to help reduce uncertainties within the preliminary ROA (anticipated data needs are listed in the body of the report);
- Clarifying the relative importance of the various pathways by which pathogens could move between lakes should be considered a high priority;
- The Great Lakes Fishery Commission should consider adopting the analytical framework developed here when evaluating other fish translocation decisions.

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DELIVERABLES

This study has resulted in the following deliverables:

1. An oral presentation (see Appendices);
2. This completion report;
3. Two manuscripts in preparation:

Fenichel, E.P., J. I. Tsao. M. Jones, and G.J. Hickling. Fish pathogen screening and the chance of moving sick fish. *In preparation for* J. Aq. Anim. Health. To be submitted: 12/2006.

Fenichel, E.P., J. I. Tsao, G. J. Hickling, and M. Jones. Real options for managing risk in irreversible fisheries management decisions. *In preparation for* Can. J. Fish. Aq. Sci. To be submitted: 2/2007.

PRESS RELEASE

Fisheries managers who need to move fish between lakes should adopt newly-developed risk management tools from the business world, say researchers from Michigan State University and the University of Tennessee. The research team, funded by the Great Lakes Fishery Commission, has been seeking ways to address concerns that moving live fish also risks moving unwanted pathogens. The team focused on the transfer of sterilized male sea lamprey from Lake Ontario to the St. Marys River - these transfers are done each year as part of the region's integrated lamprey control program. The team concluded that 'Real Options Analysis' – a technique original developed to help business managers balance risks associate with investment in real assets – was the most promising approach for managing the risks inherent in fisheries management decisions.

The appeal of the real options analysis framework addresses the problem of exercising precaution but not be "overly cautious." The team stresses that the lamprey translocation and sterilization program has benefits – it aids in Great Lakes restoration. So it is not necessarily wise to halt lamprey translocations simply because there is risk. "If the disease risk is small enough" says team member Eli Fenichel, "then a Real Options Analysis will probably conclude that the translocations should continue … because we know the translocations protect valued fish from lamprey, and that's worth a lot to some people." Mr. Fenichel says, "on the other hand, since disease introduction might be both irreversible and devastate valued fish stocks we may want to halt translocations, the problem is that there is uncertainty about which case we face, and the Real Options Analysis tells us if we are certain enough that the damages won't be too large to proceed with the translocation."

This new approach matches the amount for precaution needed with the risks that managers face. Using real options analysis managers calculate a 'precautionary multiplier' that is applied to the costs. This increases the 'costs' to account for risk, where costs are thought of as the benefits from an alternative program. The precautionary multiplier is determined based on the degree of uncertainty, and can be adjusted in light of new scientific information.

Pathogen screening can play an important role in managing the risk of pathogen transfer. The study investigated how *hard* managers should look for a pathogen. Screening is most likely to be effective when pathogen prevalence is high or the number of screened fish is a significant fraction of the number transferred. The study also considered how *long* managers should continue looking once surveys fail to find infected fish. The team suggests that screening should eventually be halted if no infected individuals are found. The length of time that screening should persist depends on screening program costs, the cost of failing to detect infected fish, and the probability that infected fish are translocated.

The current study focused on pathogen transfer risk, but the team emphasized that the insights provided can make a broader contribution to balancing risks in fisheries management.

APPENDICIES

A. Mathematical Details

The real options problem has been solved and explained in a variety of sources (see Dixit and Pindyck 1994 or Morel *et al.* 2003). Here we provide the necessary formulas for implementation.

Integrating sources of uncertainty

Stochastic events that affect the benefits from the fishery may be combined into a single multiplicative binomial process, even if some sources of uncertainty may be correlated or mean reverting (Copeland and Antikarov 2003 p. 222). This is similar to choosing an indicator variable in decision analysis, as is typically done in natural resource systems decision analyses. Geometric Brownian Motion (GBM) is an appropriate process for combining multiple sources of uncertainty (Copeland and Antikarov 2003; Morel *et al.* 2003). Under GBM, benefits trend in a general direction, but at each time step the actual benefits follow a random walk:

$$(A1) \qquad dB_{\mathrm{i}} = \alpha_i B_i dt + \sigma_i B_i dz$$

Equation (A1) is a stochastic differential equation that expresses the change in benefits where B is the value of benefits associated with management decision $i = \{\mathrm{X, H}\}$, with X and H representing the benefits associated with exercising and holding the option, respectively. The parameter α is known as the drift parameter and σ is the instantaneous volatility parameter.[17] The term dt is the time increment and dz is the increment of the Wiener process.[18] Campbell *et al.* (1997 p. 362) estimate α_i and σ_i^2 by maximum likelihood: (the index, i, has been suppressed).

$$(A2) \qquad \hat{\alpha} = \frac{1}{T}\sum_{t=1}^{T}\left\{\ln\frac{B_t}{B_{t-1}}\right\}$$

$$(A3) \qquad \hat{\sigma}^2 = \frac{1}{T}\sum_{t=1}^{T}\left[\ln\frac{B_t}{B_{t-1}} - \frac{1}{T}\sum_{t=1}^{T}\left\{\ln\frac{B_t}{B_{t-1}}\right\}\right]^2$$

where t indexes the simulation period and T is total number of periods simulated (simulation periods are often years). Smith (2005), Brandao *et al.* (2005 b), and Morel *et al.* (2003) offer alternative approaches to estimating drift and volatility parameters form simulation data.

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[17] The value of σ should not be confused with the standard deviation of B.

[18] A Wiener process is the continuous-time limit of a random walk (see Dixit and Pindyck 1994 p. 59-84). It is this process that makes (A1) a stochastic differential equation.

Computing the precautionary multiplier, Γ
As noted in Section 4.4, the expected difference between the net benefits associated with exercising and holding the option is maximized by solving for the function *F*.

(A4) $$F(B_X, B_H) = E\left[e^{-rt}(B_X - B_H)\right]$$

where *r* is the risk-free discount rate, and B_i is the expected net benefits of exercising the option (X) and holding the option (H). It should be noted that this problem is different than maximizing the expectation of {X, H}; rather, the expectation of the maximum of {X, H} is taken. By Jensen's inequality these quantities are not equivalent.

Dixit and Pindyck (1994 p. 141) explain that there are three conditions that must be meet in solving this problem, leading to two equations necessary for the calculation of the precautionary multiplier, Γ (see Dixit and Pindyck 1994 pp. 140-143 and 207-211 for solution details). These equations are:

(A5) $$\Gamma = \frac{\beta}{\beta - 1} \quad \text{where}$$

A6) $$\beta = \frac{-\left(\alpha_X - \alpha_H - \frac{\sigma_X^2 - 2\zeta\sigma_X\sigma_H + \sigma_H^2}{2}\right)}{\sigma_X^2 - 2\zeta\sigma_X\sigma_H - \sigma_H^2} \pm \frac{\sqrt{\left(\alpha_X - \alpha_H - \frac{\sigma_X^2 - 2\zeta\sigma_X\sigma_H + \sigma_H^2}{2}\right)^2 + 2(r - \alpha_H)(\sigma_X^2 - 2\zeta\sigma_X\sigma_H + \sigma_H^2)}}{\sigma_X^2 - 2\zeta\sigma_X\sigma_H + \sigma_H^2}$$

For Γ > 1, the positive root of β >>1, this also requires that $r > \alpha_H$ (Morel *et al*. 2003). Equations (A5) and (A6) can be rewritten to provide intuition about the result as a 'golden rule expression.' This is done by first solving equation (A6) for *r*, the discount rate. Then, equation (A5) is solved for $\beta = \Gamma/(\Gamma\text{-}1)$, and substituted into the solution for (A6).

(A7) $$r = \alpha_H + \frac{\Gamma(\alpha_X - \alpha_H)}{\Gamma - 1} - \frac{\Gamma\Sigma}{2(\Gamma - 1)^2} \quad \text{where } \Sigma = -\sigma_X^2 + 2\zeta\sigma_X\sigma_H - \sigma_H^2$$

In equation (A7), the discount rate *r* represents the opportunity cost of holding or exercising the option. The first two terms on the right-hand-side (RHS) are a weighted sum of the drift coefficients of holding and exercising the option. This is interpreted as the net value of having exercised the option. The first RHS term is the drift parameter or rate of return from holding the option. If $\alpha_X = \alpha_H$ and in the limit as $\Gamma \rightarrow 1$, only the first term remains. In this case the forgone returns from holding the option, *r*, in the limit must equal the gains from holding the option α_H. The second RHS term is the marginal gain from exercising the option weighted by the precautionary multiple, which accounts for the endogenous component of risk (Shogren and Crocker 1999). Notice, if Γ is close to unity the second RHS term dominates the first, 'favoring' exercise of the option. Conversely, if Γ is large then the first RHS term dominates the second, 'favoring' holding the option. The third RHS term is the total cost of risk. The term Σ is the quantity of risk and $\Gamma/2(\Gamma\text{-}1)^2$ is the cost of a unit of risk. Notice if $\sigma_X = \sigma_H$ and $\zeta = 1$, then $\Sigma = 0$ and there is there is no risk. The third term may also be interpreted as accounting for uncertainty or the exogenous component of risk. In this case it should be noted that $\Gamma/(\Gamma\text{-}1) > \Gamma/2(\Gamma\text{-}1)^2$ indicating the relative importance of endogenous risk. However, since Γ appears in both the 'endogenous' and ‘exogenous’ risk components, and condition (A7) must hold, then conditional on the decision to hold or exercise the option risk is endogenous.

Equation (A7) can be rewritten to make use of the intuition associated with the risk-adjust net present value (NPV) method:

$$\text{(A8)} \qquad r + \frac{\Gamma\Sigma}{2(\Gamma-1)^2} = \alpha_H + \frac{\Gamma(\alpha_X - \alpha_H)}{\Gamma - 1}$$

The third RHS term in equation (A7), the cost of risk, represents a risk premium when moved to the left-hand-side in equation (A8), adjusting the discount rate for risk. Riskier investments require a higher rate of return. The difference between this risk-adjust-discount rate and those applied in the risk-adjusted NPV approach is that in equation (A8) the risk premium is determined endogenously based on the uncertainty in the system and the optimal decision. That is, Γ appears on both sides of the equation so clearly calculating the risk premium requires determining the optimal decision to hold or exercise the option. Calculating the risk premium in this fashion satisfies the concerns raised by van Ewijk and Tang (2003) and Lesser and Zerbe (1994) about risk-adjusted discount rates.

B. Table A. Glossary of Terms

Term	Definition
Ammocoetes	Larval sea lamprey
Benefits	Marginal gains associated with making one decision as opposed to another, usually measured by consumer surplus.
Bioeconomic model	A model whereby ecological processes influence economic choices or economic choices influence ecological processes. A *jointly determined* bioeconomic model is one where ecological processes are influence by economic choices *and* economic choices are influenced by ecological processes.
Capital	Any resource that *i)* produces goods or services and *ii)* is not used up in the production process. For example, a fish stock is capital because if the population is held at some level through harvesting, the stock continues to produce additional fish (surplus production) that can be harvested.
Consumer surplus	The difference between the price that consumers are willing to pay for a good or service and the amount they must actually pay.
Costs	Forgone opportunities - the benefits that could have been gained by choosing something else.
Decision tree	A graphical presentation of decision nodes and their expected outcomes.
Discount rate	The rate at which future benefits are discounted.
Discounting	A process for accounting for time preference. Time preference exists because (all else equal) people prefer rewards now and damages in the future. Discounting may also be thought of as the process for accounting for the opportunity cost associated with putting off the gains until a future time period.
Disease	A clinical condition that causes mortality or morbidity in an organism
Drift	The change in an expected value for a random variable following a Geometric Brownian Motion.
Endogenous	Something (a value) derived within a model.
Geometric Brownian Motion	A way of modeling a random variable in continuous time. This is essentially a random walk.
Infinite horizon	This refers to how far into the future the manager plans. Alternatively, the planning horizon can be based on the expected life of the capital asset, so for natural resources we expect that wild populations or ecosystems can provide benefits in perpetuity if managed correctly. Therefore, the planning horizon is referred to as infinite.
Investment	Using resources to improve or gain capital.
Irreversible	A decision that once made or an event that has occurred that can not be changed back to the original state.
Jensen's inequality	$E[F(X)] \neq F(E[X])$ where X is a random variable (assuming function F is nonlinear).
Learning	The processes of reducing uncertainty.

Term	Definition
Net present value	The value of a future benefit that has been discounted to present terms.
Option	The right, but not the obligation, to do something.
Outcomes	A condition of the world experienced by society.
Pathogen	A parasitic organism that can inflict disease.
Precautionary multiplier	A weighting term that adjust costs for risk characteristics.
Precautionary principle	The concept, given prominence in the Rio Declaration, that projects involving "threats of serious or irreversible damage or lack of full scientific certainty" should *not* be untaken.
Real option	A kind of option that involves decisions about investment in real (physical) or natural capital. The term real is added to differentiate this kind of option from a financial option such as a stock option.
Real options analysis	Analysis to value, or find the optimal exercise time of, a real option.
Residual variance term	In the linear model $y = a + bx + \varepsilon$, ε is the residual variance term; it will will follow some distribution.
Resource	Refers to a specific type of capital. Therefore, natural resource refers to natural capital, while human resource refers to human capital.
Risk	The interaction between the likelihood of an event and the consequences for an individual or society associated with such an event.
SMRT	The Sterile Male Release Technique
Stochastic dynamic programming	An approach for finding a feedback rule that maximizes or minimizes the value of a function. This approach is generally used for intertemporal problems that involve uncertainty.
Structural variable	In the following linear model a and b are both structural variables: $y = a + bx + \varepsilon$, where x is the independent variable and y is the dependent variable.
Time preference	The phenomena that individuals prefer benefits today as opposed to tomorrow all else held equal.
Uncertainty	The degree of imperfection in knowledge about the way a system works.
Volatility	The deviation in the change of a random variable over time that follows Geometric Brownian Motion, often used as the best estimate of "riskiness."
Wiener process	The limit of a random walk process in continuous-time.

C. Conference presentation:

Fenichel, E.P., G. Hickling, J. Tsao, and M. Jones. 2006. Balancing the benefits, costs, and risk of fish translocation programs: the case of the sterile male sea lamprey release. The Ecological, Social and Political Challenges of Managing Landlocked Sea Lamprey Populations in the Great Lakes-St. Lawrence Basin Symposium at the American Fisheries Society Annual Meeting, Lake Placid, NY.

Translocations of live fish between water bodies are undertaken for a range of management purposes. The expected benefits associated with decisions to undertake or forgo translocations need to be balanced against costs and risks. Translocation increases uncertainty about the future of the recipient body's fisheries, but forgoing translocation may also be costly. To help balance benefit-cost tradeoffs, while accounting for future uncertainties, we have developed a general framework adaptable to a range of fish translocation programs that integrates economics, epidemiology, and ecology.

Using this framework, we examine the St. Marys River (Lake Huron) sterile male release sea lamprey control program. Sterile males are released to compete with fertile males, with control success contingent on a high sterile:fertile male ratio. Lamprey may be collected from sources outside the Lake Huron basin to obtain an ample stock for translocation. Along with the lamprey, it is possible that unique pathogens are transferred into the Lake Huron ecosystem, thereby increasing disease risk and potentially decreasing the program's benefit. Screening a sample of lampreys for pathogens decreases uncertainty and creates an opportunity to abort release, but raises program costs. We characterize criteria for decisions to undertake or forgo translocations contingent on efficient levels of screening.