A Quantitative Model for Risk-Assessment and Management of Invasive Yellow Perch

Final Report to the Pacific Salmon Commission
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Abstract

In Canada, aquatic invasive species are the second leading cause for the decline of freshwater species at risk, and the introduction of non-indigenous species represents one of the greatest threats to fish conservation. In British Columbia, there is growing concern regarding the potential impacts of invasive yellow perch (*Perca flavescens*) on Pacific salmon if yellow perch are introduced into nursery lakes, such as Shuswap Lake. Although it is difficult to predict the impact of a yellow perch invasion, it is feared that yellow perch could compete with and prey upon salmon juveniles and fry. Shuswap Lake is a very valuable salmon-producing lake in BC's interior and there could be serious ecological, economic, and social consequences if yellow perch invade this lake and establish in it.

To help estimate risks to sockeye salmon populations in Shuswap Lake associated with the invasion of yellow perch, we developed a quantitative risk-assessment model, using Bayesian decision analysis as a conceptual framework. Our model evaluated a range of management actions, including "No Action", "Education", "Enforcement", "Rotenone", and "Physical Removal", related to controlling yellow perch at different stages of invasion by estimating the effectiveness of each action at reducing ecological consequences. Ecological consequences of a yellow perch invasion were defined in terms of the proportional reduction in the abundance of adult sockeye salmon produced by Shuswap Lake. We used the photosynthetic rate (PR) model to determine what abundance of adult yellow perch would have low (less than 1 percent reduction in adult sockeye salmon), medium (1 to 5 percent reduction in adult sockeye salmon) and high (greater than 5 percent reduction in adult sockeye salmon) impacts on sockeye salmon. Those magnitudes of impacts were estimated by examining the potential effect of competition by yellow perch with juvenile sockeye. By means of workshop and written a survey, we elicited expert opinion on the probability that yellow perch will arrive in Shuswap Lake in the next 5 years (by natural dispersal and/or human introduction), and the intrinsic rate of population growth (*r*) of yellow perch once they arrive in Shuswap Lake. Our stochastic model calculated probability distributions for the abundance of adult yellow perch in Shuswap Lake 10 years after arrival. We did this by simulating the dynamics of introduced yellow perch using the logistic growth model and the probability distributions elicited from experts for the probability of arrival and the intrinsic rate of population growth.

Results of our risk-assessment model indicate that a combination of "Education", "Enforcement", "Rotenone" and "Physical Removal" management scenarios has the lowest median probability (0.143, as calculated across parameter values from all experts) that a yellow perch invasion will have high impacts on sockeye salmon, and the highest median probability (0.680) that yellow perch will have low impacts. Based on our results and the uncertainty regarding the impacts of yellow perch, we recommend that sampling in Adams Lake begin immediately to determine the abundance and population structure of yellow perch in that lake. It is important to track the rate of population increase over time because this parameter was critical in our risk assessment model for predicting the abundance and thus potential consequences of a yellow perch invasion. Sampling in Shuswap Lake is also recommended to monitor the presence of yellow perch so that removal efforts can begin immediately upon discovery of yellow perch in the lake.

This research project illustrates the value of using a quantitative framework like decision analysis to structure analyses of complex problems such as the risk assessment of yellow perch invading Shuswap Lake, a key rearing lake for major sockeye salmon populations. Much work needs to be done to improve assumptions and estimates of quantities that were input to this model, and it is hoped that this initial model structure will provide a framework for guiding future research, as well as developing an improved model in the future.

Introduction

The invasion of non-indigenous species is recognized as one of the leading threats to global biodiversity and ecosystem functioning (Sala et al. 2000). Through competition, predation, or the introduction of new pathogens, non-indigenous species can permanently alter natural ecosystems and dramatically reduce the abundance of native species (Cambray 2003). Invasive species also have large economic consequences because billions of dollars are spent on efforts to control and eradicate non-indigenous species every year (Colautti et al. 2006, Pimental et al. 2000). In Canada, aquatic invasive species are the second leading cause for the decline of freshwater species at risk, and the introduction of non-indigenous species represents one of the greatest threats to fish conservation (Dextrase and Mandrak 2006).

Invasive species include any organism introduced and established beyond their native range, whether it be from one country to another or from one region of a country to another. In Canada, yellow perch (*Perca flavescens*) are native east of the Rocky Mountains, but have extended their range westward and are now found in nearly 80 waterbodies in British Columbia (Runciman and Herborg 2008). In the absence of natural predators, yellow perch have been known to easily out-breed and out-compete native fish species and in smaller lakes can dominate the system in just a few years (Clady 1978). The concern in British Columbia is with potential impacts on Pacific salmon if yellow perch are introduced into nursery lakes, such as Shuswap Lake. Although it is difficult to predict the impact of a yellow perch invasion, it is feared that yellow perch could compete with and prey upon salmon juveniles and fry (Brown et al. 2007). Shuswap Lake is a very valuable salmon-producing lake in BC's interior and there could be serious ecological, economic, and social consequences if yellow perch invade this lake.

To develop policy and management plans that protect native fish from the arrival and spread of aquatic invasive species, the ecological risk of current and potential invaders must be assessed. This can be accomplished using ecological risk assessment, which evaluates the level of risk associated with the introduction of non-indigenous species by assessing the probability that a species will become established and the ecological consequences of that establishment (Kolar and Lodge 2002). The risk assessment process can help inform decisions and aid in allocating resources to prevent invasions or deal with ongoing invasions. To help estimate risks to salmon populations in Shuswap Lake associated with invasion of yellow perch, this research project had the following objectives:

Research Objective 1: Develop a stochastic simulation model to evaluate a range of management actions related to controlling yellow perch at different stages of invasion by estimating their effectiveness at reducing ecological consequences. Numerous sensitivity analyses from this project will illustrate for fisheries managers the magnitudes of tradeoffs between expenditures on yellow-perch control actions and the probability for each of several magnitudes of ecological consequences.

Research Objective 2: Create this model so that it can be adapted as a management tool for other freshwater systems where native fish are at risk from aquatic invasive species.

Methods

Risk Assessment Model

To help estimate risks to salmon populations in Shuswap Lake associated with the invasion of yellow perch, we developed a quantitative risk-assessment model. We used Bayesian decision analysis as a conceptual framework for this model (Figure 1) to ensure that uncertainties were taken into account and reflected in the outcomes of our analysis.

Management Objectives

To initiate this project, we used the following management objective in our decision analysis.

- Minimize the abundance of adult yellow perch in Shuswap Lake over the next 10 years.

Management Scenarios

Our analysis included five alternative management actions representing a range of possible control methods for reducing the ecological impacts of invasive yellow perch. These actions are “No action”, “Education”, “Enforcement”, “Rotenone”, and “Physical Removal”. Detailed description of these actions can be found in Table 1. Each action is intended to control a different stage of the invasion process. For example, “Education” is intended to prevent the arrival of yellow perch in Shuswap Lake, whereas “Physical Removal” is intended to control the establishment and spread of yellow perch after they have arrived in Shuswap Lake. By combining multiple management actions, all three invasion stages can be controlled in a single management scenario, as shown in Table 1.

Uncertain States of Nature

The uncertain states of nature included in our risk-assessment model are the first three stages of invasion, arrival, survival, and reproduction, as outlined in the “National guidelines for assessing the biological risk of aquatic invasive species in Canada” (Mandrak and Cudmore 2006). These uncertain states of nature were defined by probability distributions elicited from experts.

The first stage of the invasion process, arrival, is represented in the model by the “probability of arrival”. We defined this uncertain parameter as the probability that a sufficient number of yellow perch (i.e. minimum number required to create an established population) will arrive in Shuswap Lake in the next 5 years. The arrival of yellow perch in Shuswap Lake could occur by natural dispersal from nearby lakes or by unauthorized human introductions. Since these two different vectors of arrival are controlled by different management actions, we divided the probability of arrival into the “probability of arrival via human introduction” and the “probability of arrival via natural dispersal”, and we elicited separate probability distributions for each parameter from experts.

The survival and reproduction stages have been combined because together they constitute what is considered the establishment phase. This stage of the invasion process is represented in the model by a population growth parameter, the observed “intrinsic rate of natural increase” or “intrinsic rate of population growth” (r). This rate can be thought of as the per-capita reproductive rate minus the per-capita death rate (or the net gain per year in number of fish divided by the number of fish in the previous year). In this case, we were interested in the intrinsic rate of population growth of yellow perch once they have arrived in Shuswap Lake.

Invasive species often show exponential population growth when they first enter new habitat, so the most important uncertain parameter in our model was the intrinsic rate of increase. It has been shown that establishment of an immigrant/non-native species is less likely if the intrinsic rate of increase (*r*) of that species is small (Lawton and Brown 1986). The probability distribution for this uncertain parameter, *r*, was used in our risk-assessment model to simulate the population growth of yellow perch to determine the abundance of yellow perch in the next 10 years if yellow perch arrive in Shuswap Lake. We used a simple logistic growth model:

(1) $$\mathbf{N_{t+1} = N_t + \mathit{r}N_t(1\text{-}N_t/\mathit{K})}$$

Where N_0 is the initial number of yellow perch introduced into Shuswap Lake, *r* is the intrinsic rate of growth, and *K* is the environmental carrying capacity of Shuswap Lake for yellow perch. Values for N_o and *K* were elicited from experts and the range of values they provided were used to inform our sensitivity analysis.

Ecological Consequences

Our stochastic model calculated probability distributions for the abundance of adult (age 2+) yellow perch in Shuswap Lake 10 years after arrival. It did this by simulating the dynamics of introduced yellow perch using the logistic growth model and the probability distributions for the probability of arrival and the intrinsic rate of population growth elicited from experts. The model produced distributions of the weighted average probabilities of abundance of adult yellow perch for each expert under each management scenario (Table 1). This enabled us to determine which management scenario best satisfies the management objective. We undertook sensitivity analysis designed to look at the effects of various parameters of the growth model on the rank order of management options. We ran our simulation model with various values for N_0 and *K* elicited from experts.

The magnitude of ecological consequences that a yellow perch invasion could have in Shuswap Lake was based on the abundance of adult yellow perch 10 years after arrival. There are three possible categories of consequences: high, medium, and low. We assumed that the greater the abundance of perch the greater the ecological consequences and the greater impact they will have on salmon. It is uncertain whether adult yellow perch will inhabit the pelagic zone of Shuswap Lake, or restrict themselves to the littoral zone. Since juvenile sockeye salmon in Shuswap Lake inhabit primarily the pelagic zone of the lake, the impacts on sockeye would be potentially great if adult yellow perch utilize the pelagic zone. For this reason, we have focused on the possibility of adult yellow perch becoming pelagic and the outcomes of our risk-assessment model are based on this assumption. Ultimately the goal is to minimize the ecological impact of yellow perch on salmon by minimizing the abundance of adult yellow perch using different management actions. More detailed measures of ecological consequences are not easily quantifiable at this stage due to the complex ecological interactions about which little is known. We therefore limited our analyses to these indirect measures of the potential impact on Pacific salmon.

We used the photosynthetic rate (PR) model as described in Hume et al. (1996) to calculate the carrying capacity of yellow perch in Shuswap Lake and the abundance of adult yellow perch that would lead to low, medium, and high impacts on adult sockeye salmon as defined by workshop participants. Based on Shuswap Lake's productivity, as estimated by Shortreed et al. (2001), the PR model can be used to calculate the biomass of juvenile sockeye salmon the lake can sustain. Because of the lack of information on interactions among yellow perch and sockeye salmon, we made the simplest assumption, that juvenile sockeye salmon would consume the same amount of prey per unit juvenile salmon biomass as the equivalent biomass of yellow perch. Thus, we assumed that the biomass of juvenile sockeye salmon produced by Shuswap Lake could equal the total biomass of pelagic adult yellow perch that could be supported by the lake if there were no sockeye. In this way, we were able to use the PR model to predict what abundance of adult yellow perch would reduce the adult sockeye salmon population produced by Shuswap to the levels defined by the low, medium, and high impacts. Note that this method implicitly also assumes that there is no density-dependent survival of sockeye salmon between the juvenile stage in the lake and the time when mature adults return to coastal fishing areas. In our calculations, we used a sockeye fry mean weight of 2.6 g (Hume et al. 1996) and a weighted average of yellow perch weight of 164 g. The weighted average of yellow perch weight was calculated using age structure (Paukert and Willis 2001) and mean weight-at-age values (Thorpe 1977) for yellow perch.

Expert Elicitation

Workshop

In July 2008, a workshop was held in Kamloops, BC, for 8 federal and provincial fisheries scientists and managers involved in the management of sockeye salmon and/or invasive yellow perch in the Thompson region. The primary objective of the workshop was to conduct a trial run of our elicitation procedure (see Part 1 of the survey described below), so that adjustments could be made before distributing the survey to yellow perch experts in eastern Canada and western United States (the latter region being an area where yellow perch have invaded already). We were also interested in defining the ecological impact categories, i.e. what percent reduction in adult sockeye salmon would be considered by managers to be a high, medium, or low impact.

Survey

In addition to obtaining information at this workshop, we developed a two-part written “Yellow Perch Risk Assessment Survey” that was sent to federal, provincial, and state fisheries scientists and managers, as well as university fisheries scientists, who have experience with yellow perch in their native and introduced ranges. This survey contained considerable background information on the yellow perch and salmon situation in BC and Shuswap Lake (a copy of that information is available upon request). We asked these experts to extrapolate their experiences with yellow perch to the possibility of a yellow perch invasion in Shuswap Lake. Part 1 of the survey was designed to elicit probability distributions for each uncertain state of nature under each different management scenario. We used the Bayesian view of probability, which defines the probability of some parameter value as the degree of belief that a person has that the value is the true one in nature, given all the relevant information currently known to that person (Morgan and Henrion 1990). Thus, the probability distributions elicited from the survey participants represented their degree of belief in the true value of the uncertain parameters. We elicited cumulative probability distributions (or cumulative distribution functions (CDFs)) in Part 1 of the survey, because extensive experience has shown that results are more consistent when experts are asked to provide estimates of uncertain quantities through drawing CDFs rather than drawing probability density functions (PDFs) directly (Keeney and von Winterfeldt 1991). We elicited CDFs using the fractile method described in DeWispelare et al. (1995) and converted these into PDFs in order to input them into our risk-assessment model. Example questions from Part 1 of the Yellow Perch Risk Assessment Survey can be found in Appendix A1. An example of the spreadsheet template provided for experts to record their responses can be found in Appendix A2.

The second part of the survey, Part 2, consisted of a brief online questionnaire designed to elicit a variety of qualitative and quantitative information regarding the potential behaviour of yellow perch once they arrived in Shuswap Lake. For example, we asked experts to describe what factors they believed could lead adult yellow perch to utilize the pelagic zone rather than the littoral zone. We used a web-based survey host called Survey Monkey. See Appendix B for example questions from Part 2 of the Yellow Perch Risk Assessment Survey. The survey was sent out in August 2008 to 35 individuals who had previously been contacted and agreed to take part in the survey.

Results

Expert Elicitation

Workshop

At the workshop, the 8 participants defined the ecological consequences of a yellow perch invasion in Shuswap Lake in terms of the proportional reduction in the abundance of adult sockeye salmon. Participants defined a low impact as a less than 1 percent decrease in adult sockeye salmon abundance, a medium impact to be between 1 and 5 percent reduction, and a high impact to be anything greater than a 5 percent reduction in adult sockeye abundance from Shuswap Lake. The workshop participants also provided feedback on Part 1 of our survey (Appendix A1 and A2), and identified a number of questions that we subsequently inserted into Part 2 of the Yellow Perch Risk Assessment Survey (Appendix B), which was the on-line, web-based survey.

Survey

We received 8 written responses to Part 1, and 12 responses to Part 2 of the Yellow Perch Risk Assessment Survey. Probability distributions for the uncertain parameters elicited in Part 1 of the survey are summarized in Figures 2, 3, and 4. The wide range of probability distributions elicited from experts indicates how much uncertainty there is regarding the invasion of yellow perch in Shuswap Lake. The experts' responses cover nearly the entire range of possibilities, which shows either (a) that the background information we provided was unclear and confusing, or (b) more likely, that there is simply too little concrete evidence for experts to draw upon i.e. not enough is known about the specific situation in Shuswap Lake.

In Part 2 experts provided estimates of the initial number of yellow perch (N_0) they believed would be necessary for perch to successfully reproduce and establish in Shuswap Lake. Two experts believed it would take less than 10 yellow perch to establish a reproducing population, while one expert believed it would take more than 100. The other nine experts were split, with four experts believing it would take between 10 and 50 individuals, and the other five believing it would take between 50 and 100 yellow perch to successfully establish a population in Shuswap Lake. These N_0 values were used as the initial starting values for the logistic growth models in a series of sensitivity analyses. Experts also provided minimum, mean, and maximum estimates of the carrying capacity (K) of yellow perch in Shuswap Lake. Once again the responses were quite varied, and we drew upon the range of estimates to inform our sensitivity analysis.

Survey participants were equally split on their views regarding whether yellow perch would inhabit the littoral and/or pelagic zone of Shuswap Lake. Six out of twelve experts believe that adult yellow perch will inhabit the littoral and pelagic zones in Shuswap Lake, while the other six experts believe adult yellow perch will be limited to the littoral zone. According to participants the most likely factors that would lead adult yellow perch to become pelagic are higher prey abundances and fewer predators in the pelagic zone. High temperatures in the littoral zone, as well as the size of the lake (large) and the size of the littoral zone (small) were also factors that experts believe could cause adult yellow perch to become pelagic.

Risk Assessment Model

PR Model

Using the PR model (Hume et al. 1996) we calculated the carrying capacity (K) of yellow perch in Shuswap Lake to be 1,380,000 adult yellow perch (age 2+). This K value was then used in the logistic growth model (equation 1) to calculate the abundance of yellow perch in Shuswap Lake 10 years after arrival. We also used the PR model, along with the definitions of high, medium, and low impacts on adult sockeye salmon abundance defined by workshop participants, to determine that an abundance of less than 20,000 adult yellow perch would lead to a low impact, an adult abundance between 20,000 and 75,000 would lead to a medium impact, and a yellow perch population greater than 75,000 adults would lead to a high impact on sockeye salmon (Table 2).

Ecological Consequences

Figure 5 summarizes the probability distributions of adult yellow perch abundance calculated by our stochastic simulation model for each expert under each of the 7 management scenarios in Table 1. Results of our risk-assessment (decision analysis) model indicate that the "No Action" scenario has the highest median probability (0.591, as calculated across all experts), that a yellow perch invasion will have high ecological consequences, while the "Four Management Actions" scenario has the lowest median probability (0.143) of that outcome (Figure 6). The "No Action" scenario also has the lowest median probability (0.266) that yellow perch will have a low impact on sockeye salmon, while the "Four Management Actions" scenario has the highest median probability (0.680) of that desirable outcome on sockeye salmon (Figure 6). The "Education" and "Enforcement" scenarios appear to perform nearly equally, and are only slightly better than the "No Action" scenario at reducing the probability of high ecological consequences (Figure 6). The "Rotenone" and "Physical Removal" scenarios perform better than "Education" and "Enforcement", but it is ultimately the combination of all four management actions, the "Four Management Actions" scenario, that best achieves the reduction of ecological consequences resulting from a yellow perch invasion in Shuswap Lake. The second best management scenario is the "Three Management Actions" scenario.

Management Costs

The costs of dealing with invasive yellow perch in BC would be incurred primarily by BC's Ministry of the Environment, who are charged with managing fisheries in the province, however, there is the possibility that the federal Department of Fisheries and Oceans could be involved in sharing some of the costs. We used costs estimated by workshop participants and other experts. As shown in Table 3, the "Education" and "Enforcement" management scenarios have the lowest annual costs, estimated at $50,000/year and $250,000/year respectively. The annual cost of "Education", includes the cost of educational materials (posters, brochures, key chains and signs), the cost of the RAPP (Report All Poachers and Polluters) information van attending 12 community events, as well as the labour costs involved in preparing documents and presentations, and attending public meetings. In addition to the yearly cost of the "Education" scenario, there would also be a one-time cost of $20,000 for the development of an education program for schools. The implementation costs of this program are unknown.

The annual cost of "Enforcement" includes the salary of one additional conservation officer, and their transportation costs (i.e. truck, boat, and gasoline). If two additional conservation officers are hired the annual costs of the "Enforcement" scenario would double. Also included in this scenario is the possibility of paying out a $20,000 reward for information leading to the conviction of someone transporting and dumping non-native fish species.

The “Rotenone” management scenario is estimated to cost $375,000/year over 4 years in order to treat all the lakes in the Thompson region that contain yellow perch and have potential downstream connections to Shuswap Lake. This includes Skmana Lake ($200,000), Forest Lake ($250,000), Nellies Lake ($15,000), and Gardom Lake ($500,000), as well as Phillips, Fleming, Skimikin, and Miller Lakes ($500,000). The cost of the “Rotenone” scenario includes not only the cost of the chemical itself, but also the cost of all the necessary equipment (boats, trucks, sprayers, etc.), fuel, food, and water for citizens residing on the lake.

The “Physical Removal” management scenario is estimated to cost between $250,000 and $500,000/year, however, the cost of this management scenario will depend heavily on the specific removal method (i.e. gillnetting, trapping etc.) and the effort necessary to remove a sufficient number of yellow perch (i.e. enough yellow perch to reduce population growth and prevent spread).

The two combinations of management actions that we explored had higher financial costs. The combination of “Education”, “Enforcement”, and “Rotenone” is estimated to cost between $675,000 and $925,000/year for the first 4 years, after which time, the cost would decrease to between $300,000 and $625,000/year. The final management scenario, a combination of “Education”, “Enforcement”, “Rotenone”, and “Physical Removal”, is the most costly management scenario, estimated at $925,000 to $1,425,000/year for the first 4 years, after which time the cost would decrease to between $550,000 to $1,050,000/year.

Sensitivity Analysis

We conducted several sensitivity analyses to investigate the impact of certain model parameters on the results of our risk-assessment model. We investigated a range of possible carrying capacity (K) values for yellow perch in Shuswap Lake, including 31,000, 155,000, 775,000, 3,100,000, and 7,750,000, in addition to the baseline K value (1,380,000) calculated using the PR model. The results of this analysis indicate that the K value used in the logistic growth model does not alter the outcome of our risk-assessment model and does not change the rank order of management actions. When the carrying capacity of yellow perch is 775,000 (Figure 7), which is approximately half the baseline K value, the median probability across all experts of high, medium, and low ecological consequences is nearly identical to that calculated using K = 1,380,000 (Figure 6). When the carrying capacity of yellow perch increased to 3,100,000 (Figure 8), approximately double the baseline K value, the results are again similar to the original analysis, and the rank order of actions is identical.

Discussion

The results of our quantitative risk-assessment model indicate that the consequences of a yellow perch invasion in Shuswap Lake would be best mitigated by undertaking a combination of “Education”, “Enforcement”, “Rotenone”, and “Physical Removal”, i.e. the “Four Management Actions” scenario. This scenario performs best to meet our management objective of minimizing the abundance of adult yellow perch in Shuswap Lake. While this scenario has the highest implementation costs of all the management scenarios, it reduces the median probability across all experts of high ecological consequences nearly 45% more than the “Three Management Actions” and the “Rotenone” scenarios. These results emerged despite the wide range of expert opinions about (1) the probabilities of arrival via natural or human introductions, and (2) the intrinsic rate of population growth of yellow perch. These results strongly support the actions currently being taken by the BC Ministry of the Environment

(MOE) to inhibit the introduction of yellow perch into Shuswap Lake. However, if yellow perch do make their way into Shuswap, managers will have make the trade-off between the cost of controlling invasive yellow perch via physical removal, the most costly management action, and the economic and ecological costs of reducing adult sockeye salmon populations produced by Shuswap Lake.

When we distributed our survey in August, 2008, yellow perch had not yet made their way into Adams Lake, a water body directly connected to Shuswap Lake via the Adams River. In early September, 2008, MOE confirmed the presence of yellow perch in Adams Lake. Although we can only speculate how this information would change the responses of our survey participants, it is possible that experts would have had a higher degree of belief in higher estimates for the probability of arrival via natural dispersal and/or human introduction of yellow perch, which in turn could have increased the probability of ecological consequences for sockeye salmon.

One lesson learned from this research is that expert elicitation of complex information is very difficult to obtain via a mail-out survey. We received feedback that we did a good job of presenting the background information in a clear manner, and that the detailed instructions on how to complete the survey were also clear. However, many people thought that there was an overwhelming time commitment expected to complete Part 1 of the survey (which led them through steps to derive their cumulative probability distributions for several uncertain quantities for each of the 7 categories of management actions). In the future, this form of complex information would be best elicited in person, either in a one-on-one or group setting like our successful workshop in Kamloops. If funds had permitted, it would have been best to gather all the experts from eastern Canada and western United States for a one-day workshop, but our limited budget precluded this step.

Recommendations

Obviously the number of large uncertainties about inputs to our risk assessment strongly suggests that a main part of our recommendations should relate to top research priorities for future data collection. Based on our results and the uncertainty regarding the impacts that yellow perch will have on sockeye salmon if they establish in Shuswap Lake, we recommend the following research priorities.

Sampling in Adams Lake should begin immediately to determine the number of yellow perch currently in the lake, and to estimate the annual rate of population increase over time. The intrinsic rate of increase of yellow perch was perhaps the most critical parameter in our risk-assessment model, and having a good estimate of this parameter would provide managers with more accurate predictions of yellow perch abundance if they arrive in Shuswap Lake, even if uncertainty about this parameter did not affect our rank order of management options. It is important to undertake sampling efforts in Adams Lake, because the arrival of yellow perch is relatively recent, and the intrinsic rates of increase in Adams Lake could be similar to those in Shuswap Lake during the early stages of a possible yellow perch invasion. Sampling in Adams Lake, or other large BC lakes with confirmed yellow perch populations, is also recommended so as to estimate the age structure of yellow perch populations in BC. Having a good estimate of the age structure would help estimate the intrinsic rate of increase, if we can tell what portion of the yellow perch population is new recruits each year. Sampling in Adams Lake should also be carried out with the intention of determining whether adult yellow perch inhabit the littoral and/or pelagic zones of the lake, as the results of our survey indicate the experts are equally split over whether adult yellow perch will become pelagic in Shuswap Lake or remain only in the littoral zone. This is important because it would help determine whether yellow perch could have a direct habitat overlap with sockeye salmon juveniles in Shuswap Lake.

We also recommend experimenting now with different methods to physical remove yellow perch from Adams Lake or another BC lake with yellow perch. Experimental removals would indicate the most effective methods and what amount of effort and financial support would be needed to keep yellow perch population levels low. This information would be very useful if yellow perch make their way into Shuswap Lake. It is also recommended that sampling be carried out in the Adams River and in Shuswap Lake so as to track the spread of yellow perch from Adams Lake into Shuswap. It is essential to monitor Shuswap Lake for the presence of yellow perch, so that physical removal efforts can begin immediately upon discovery that they are in the lake.

Two other research projects that would provide managers with more information on the behaviour of invasive yellow perch, but that are not necessarily high priorities, would be a mark-recapture study to determine the spread rates and patterns of yellow perch and a stomach content analysis of yellow perch in Adams Lake to determine whether or not yellow perch will be in direct competition with juvenile salmon in Shuswap Lake.

Conclusion

This research project illustrates the value of structuring complex problems, such as the risk assessment of yellow perch invading Shuswap Lake in terms of a quantitative framework like decision analysis. There are several uncertainties, and many of them are large, yet some ranking of management options is still possible. Equally important is the ability of decision analysis to stimulate discussion and thinking about all components of the system, ranging from clear articulation of management objectives that have measurable indicators, to identification of system components about which little is known but which are critically important (such as the probability that the yellow perch will mainly be pelagic and thereby compete with juvenile sockeye salmon, as opposed to occupying the littoral zone, where they will not be competitors with sockeye). Much work needs to be done to improve assumptions and estimates of quantities that were input to this model, and it is hoped that this initial model structure will provide a framework for guiding future research, as well as developing an improved model in the future.

Tables

Table 1. Description of management actions included in analysis and the stages of invasion they are intended to control.

Management Scenarios	Action taken to control:			Description
	Arrival in Shuswap Lake	**Abundance** (survival and reproduction)	**Spatial Distribution** (spread)	
No Action				In this scenario no action would be taken by provincial fisheries managers to prevent the arrival, establishment, and spread of yellow perch in Shuswap Lake. You can think of this management scenario as a baseline case for a yellow perch invasion, where the invasion is allowed to take its course without any intervention by fisheries managers.
Education	X			In this scenario, provincial fisheries managers would undertake a public awareness and education program in an attempt to prevent the human introduction of yellow perch into Shuswap Lake. If yellow perch do make their way into Shuswap no action would be taken by fisheries managers to control their abundance or their spatial distribution throughout the lake.
Enforcement	X			In this scenario, the enforcement of fish introduction and transfer regulations by provincial conservation and fishery officers would be increased in an attempt to prevent the human introduction of yellow perch into Shuswap Lake. If yellow perch do make their way into Shuswap Lake, no action would be taken by fisheries managers to control their abundance or their spatial distribution throughout the lake.
Rotenone	X			In this scenario, provincial fisheries managers would apply Rotenone to all lakes in the Thompson region containing established yellow perch populations in an attempt to prevent the natural dispersion of yellow perch into Shuswap Lake. If yellow perch do make their way into Shuswap Lake, no action would be taken by fisheries managers to control their abundance or their spatial distribution throughout the lake.
Physical Removal		X	X	In this scenario, no action would be taken by provincial fisheries managers to prevent yellow perch from entering Shuswap Lake. If yellow perch do make their way into Shuswap Lake fisheries managers would physically remove perch from the lake using mechanical methods in an attempt to eradicate and/or control yellow perch populations.
Three Management Actions	X			Education, Enforcement, and Rotenone scenarios as described above.
Four Management Actions	X	X	X	Education, Enforcement, Rotenone, and Physical Removal scenarios as described above.

Table 2. The abundance of adult yellow perch in Shuswap Lake leading to low, medium, and high ecological consequences for adult sockeye salmon produced by the lake.

Ecological Consequences	**Abundance** (number of adult yellow perch)	**Impact on Salmon** (proportional reduction in abundance of adult sockeye salmon)
Low	< 20,000	< 1%
Moderate	20,000 - 75,000	1-5%
High	> 75,000	> 5%

Table 3. The median probability (across all experts) of low, medium and high ecological consequences on adult sockeye salmon resulting from a yellow perch invasion in Shuswap Lake under different management scenarios and the associated cost per year and duration (number of years) of each scenario.

Management Scenarios	**Probability of Ecological Consequences**			**Management Costs** ($1000s)	**Number of Years and Cost** ($1000s)
	Low	**Med**	**High**		
No Action	0.266	0.172	0.591	$0/year	0
Education	0.352	0.153	0.541	$50/year + $20 one-time cost	Every year or until yellow perch no longer a threat
Enforcement	0.354	0.142	0.471	$250-$500/year + $20 one-time cost	Every year or until yellow perch no longer a threat
Rotenone	0.478	0.123	0.427	$375/year	4 years
Physical Removal	0.488	0.185	0.212	$250-$500/year	Every year or until yellow perch eradicated from Shuswap Lake
Three Management Actions	0.526	0.101	0.419	$675-$925/year	4 years, then $300-$625/year every year or until yellow perch no longer a threat
Four Management Actions	0.680	0.108	0.143	$925-$1425/year	4 years, then $550-$1050/year every year or until yellow perch no longer a threat

Figures

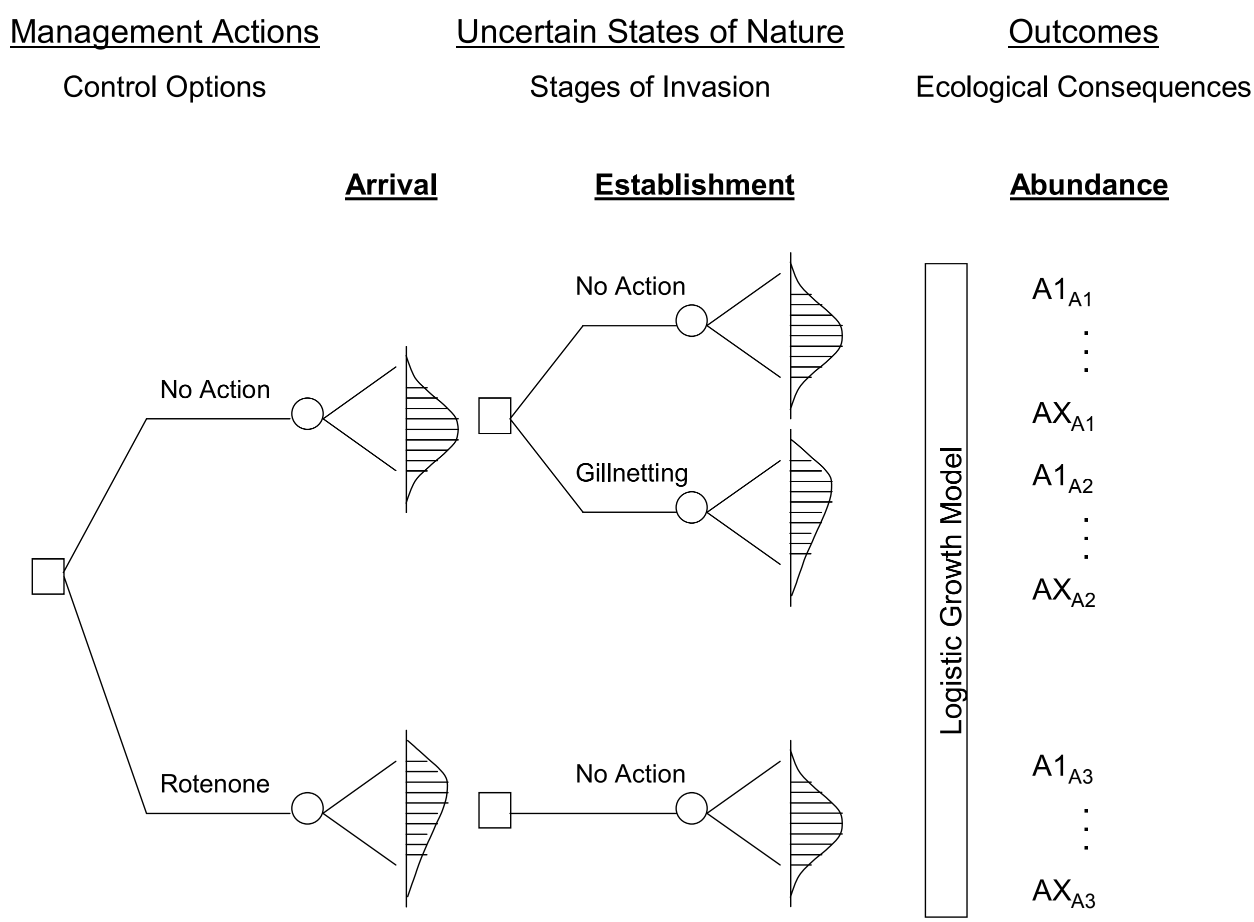
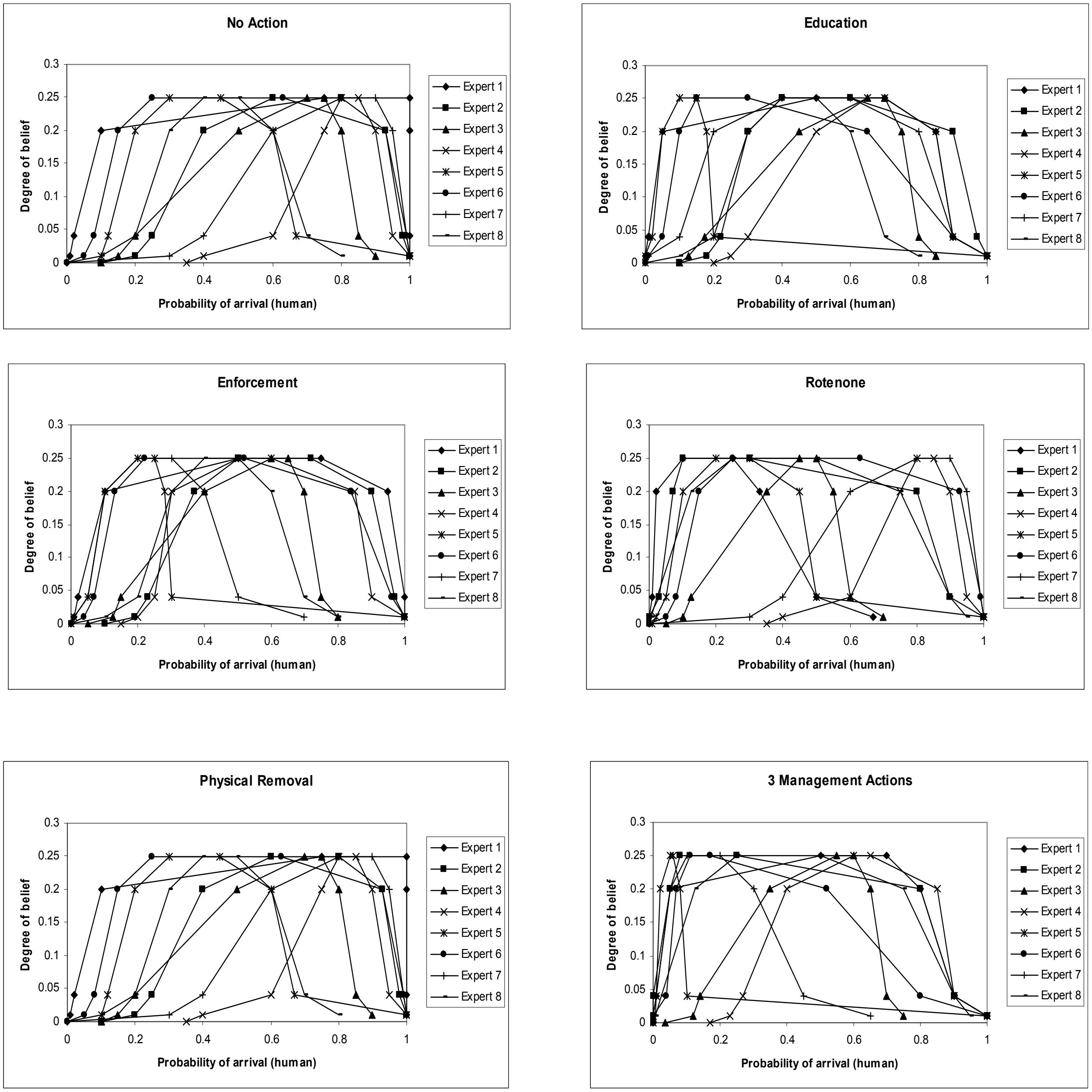


Figure 1. Conceptual representation of stochastic simulation model using a decision analysis framework. Circles represent uncertainty nodes, squares represent management decision nodes. The probability distributions representing the uncertainties (some of them purposely skewed) are shown rotated 90° clockwise from horizontal in order to conform with the conventions for drawing decision tree.



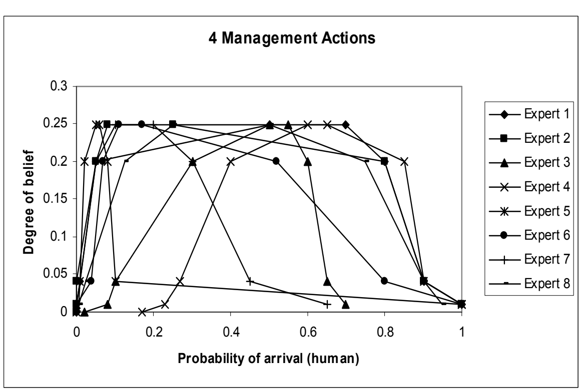
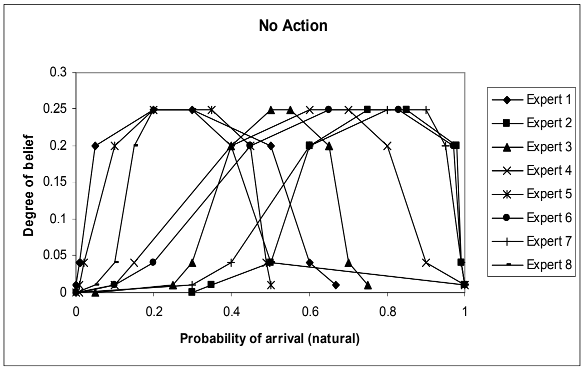
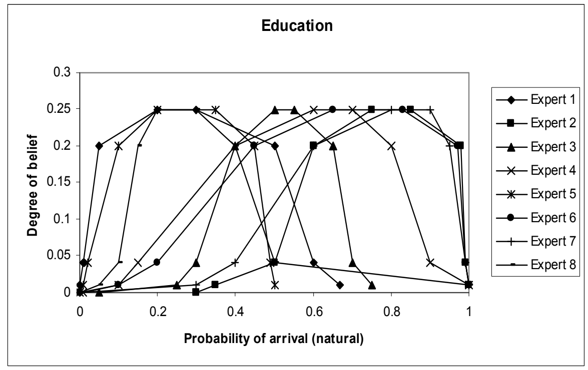
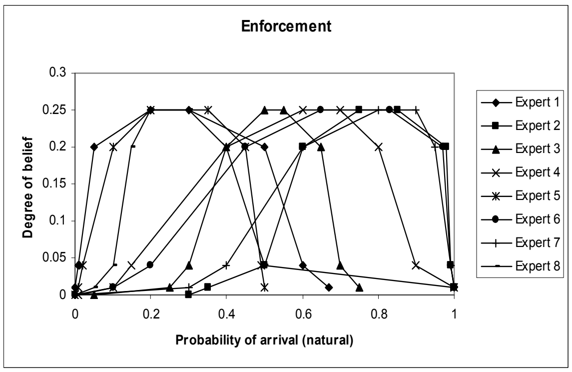
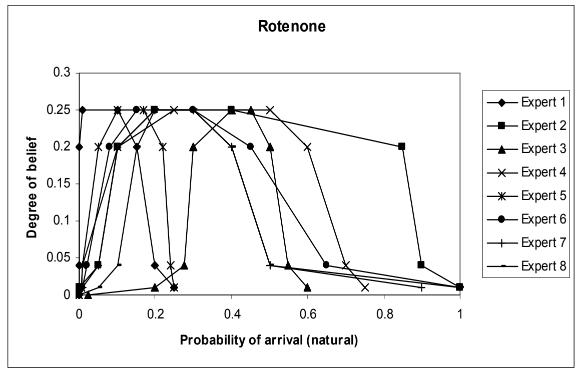


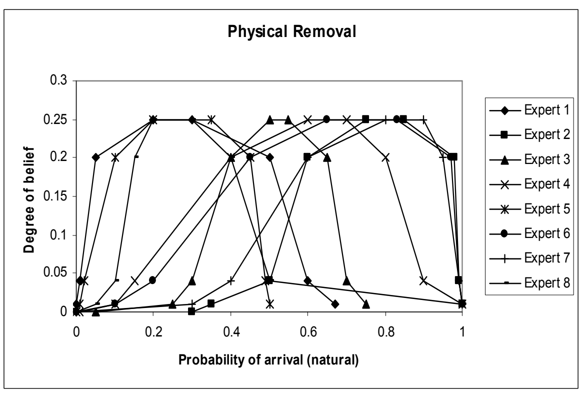
Figure 2. Probability distributions describing experts' degree of belief in the uncertain parameter, the probability of arrival via human introduction of yellow perch in Shuswap Lake in the next 5 years. Distributions shown for each management scenario.

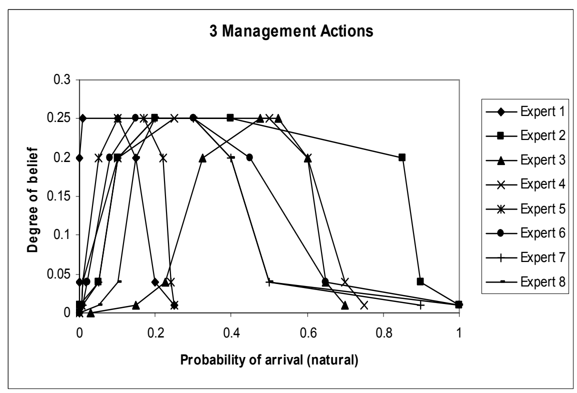












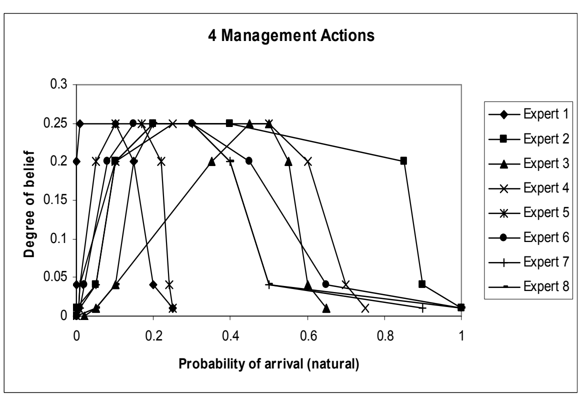
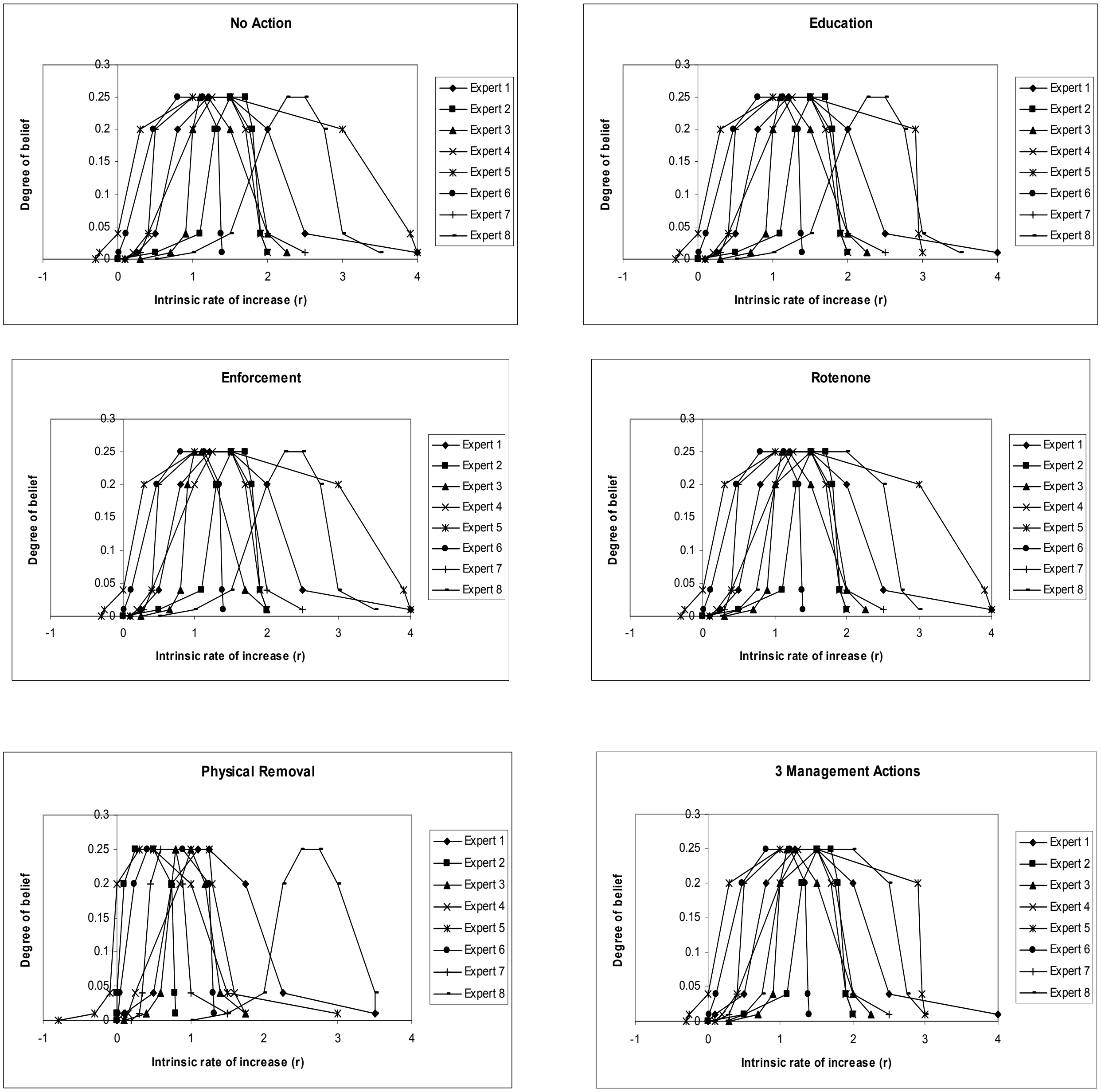


Figure 3. Probability distributions describing experts' degree of belief in the uncertain parameter, the probability of arrival via natural dispersal of yellow perch in Shuswap Lake in the next 5 years. Distributions shown for each management scenario.



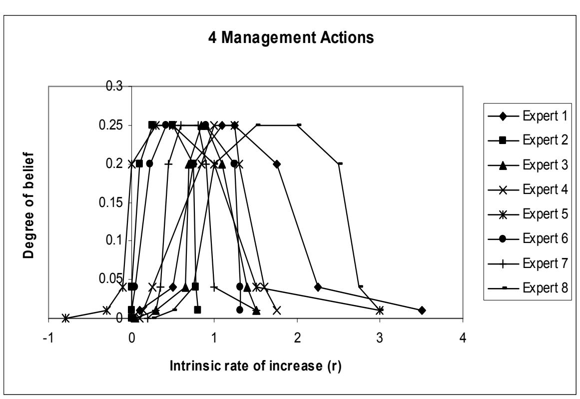
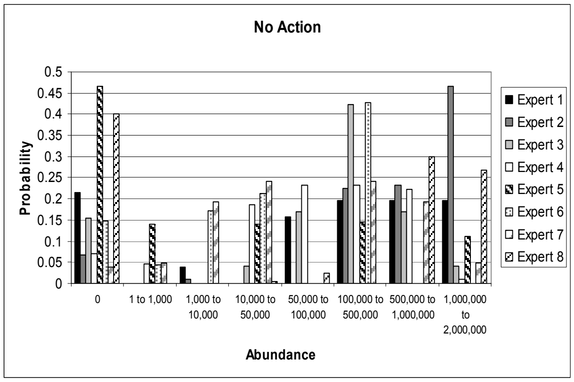
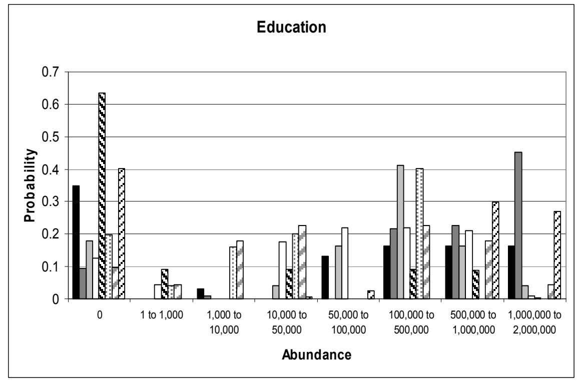
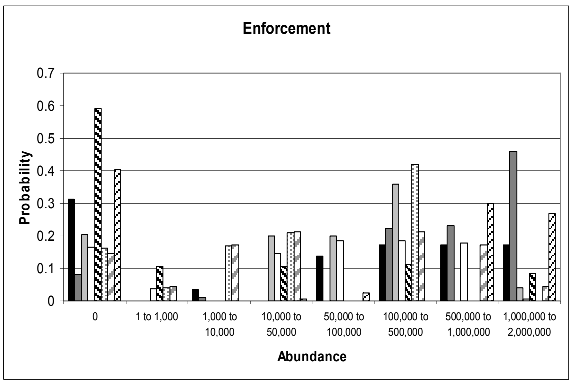
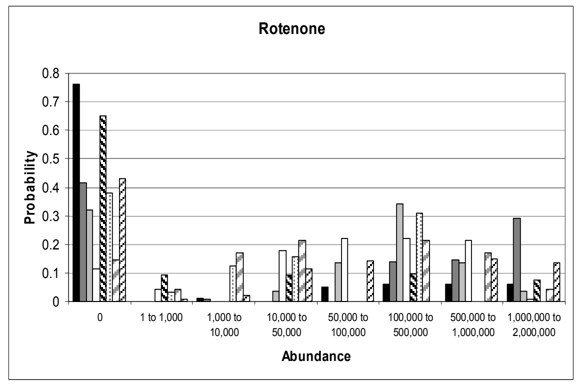


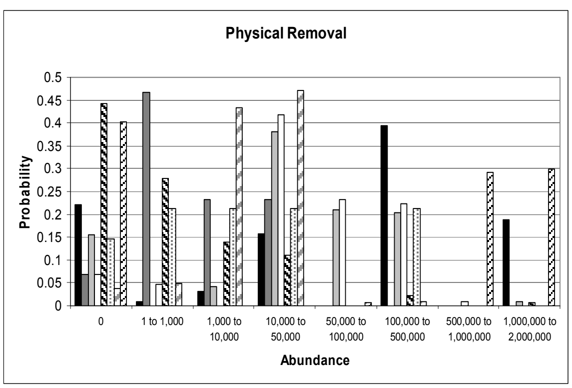
Figure 4. Probability distributions describing experts' degree of belief in the uncertain parameter, the <u>intrinsic rate of increase</u> of yellow perch in Shuswap Lake. Distributions shown for each management scenario.

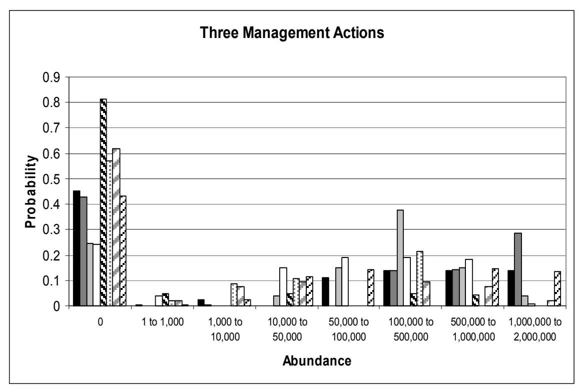












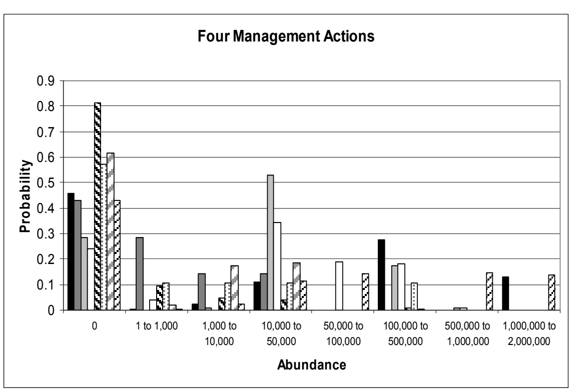


Figure 5. Probability of abundance of adult yellow perch in Shuswap Lake 10 years after arrival, for each expert across all management scenarios.

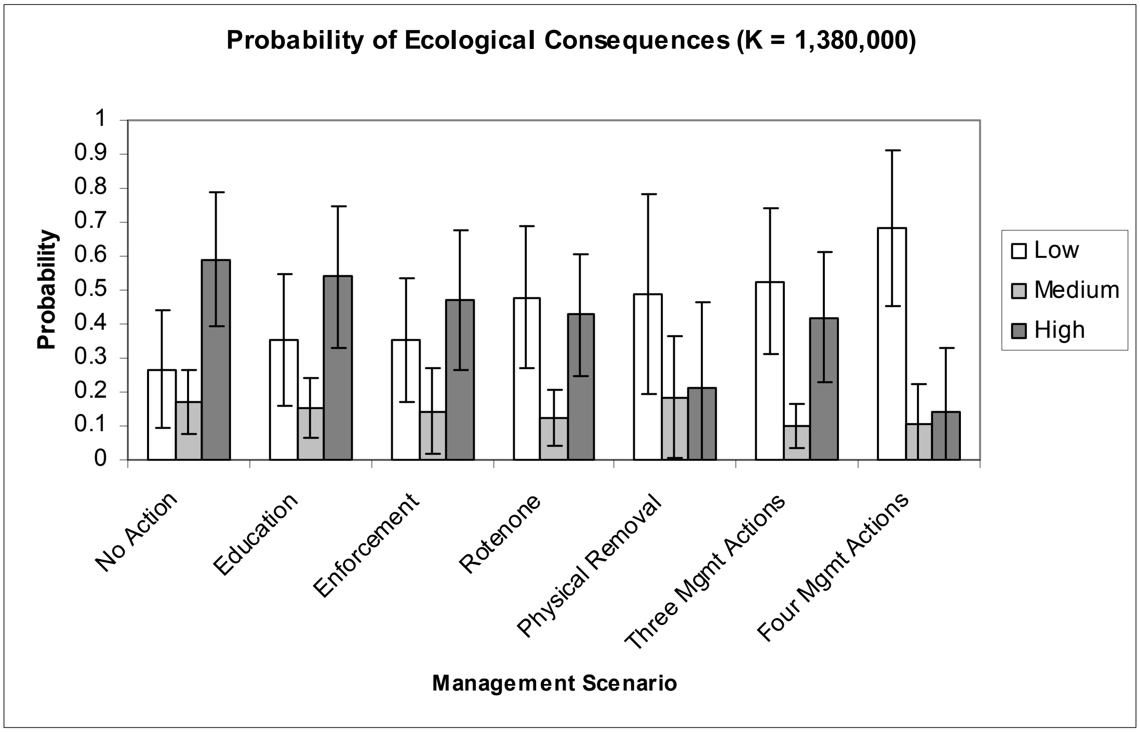


Figure 6. Median probability (across all experts) of low, medium, and high ecological consequences resulting from the invasion of yellow perch in Shuswap Lake under different management scenarios. Error bars indicate standard deviation. Results are for the case with the carrying capacity parameter for yellow perch, K, set to its baseline value of 1,380,000.

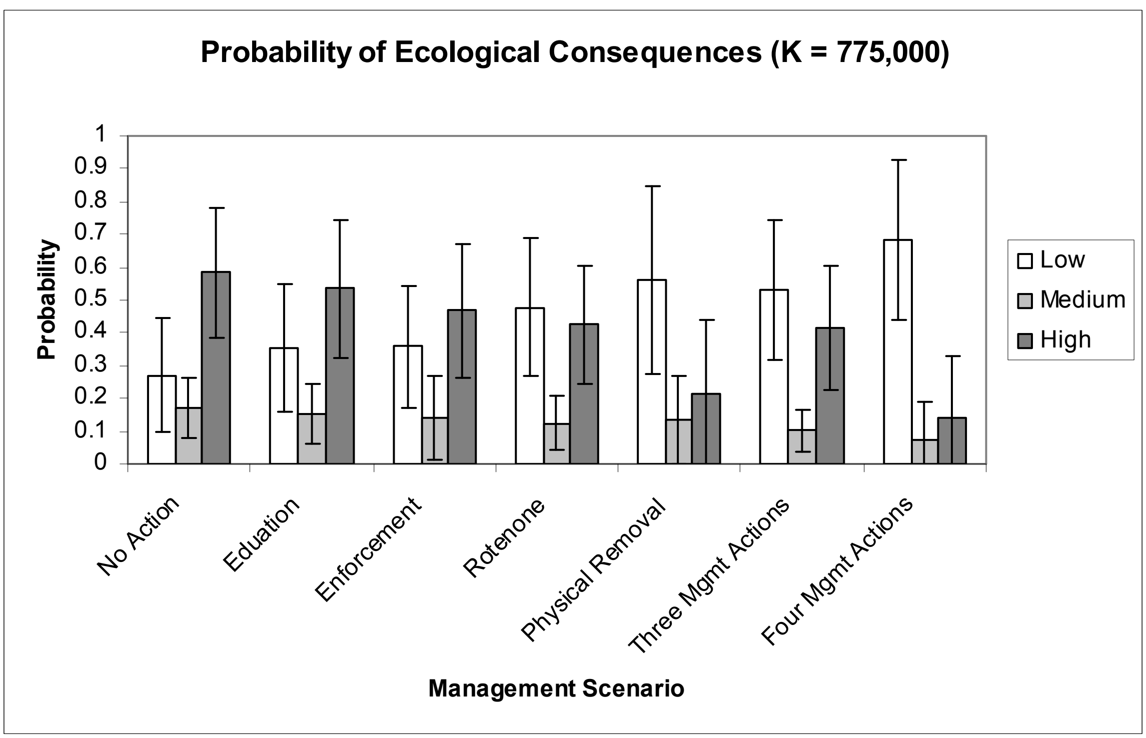


Figure 7. Same as Figure 6 except here the carrying capacity parameter for yellow perch, K, is set to 775,000.

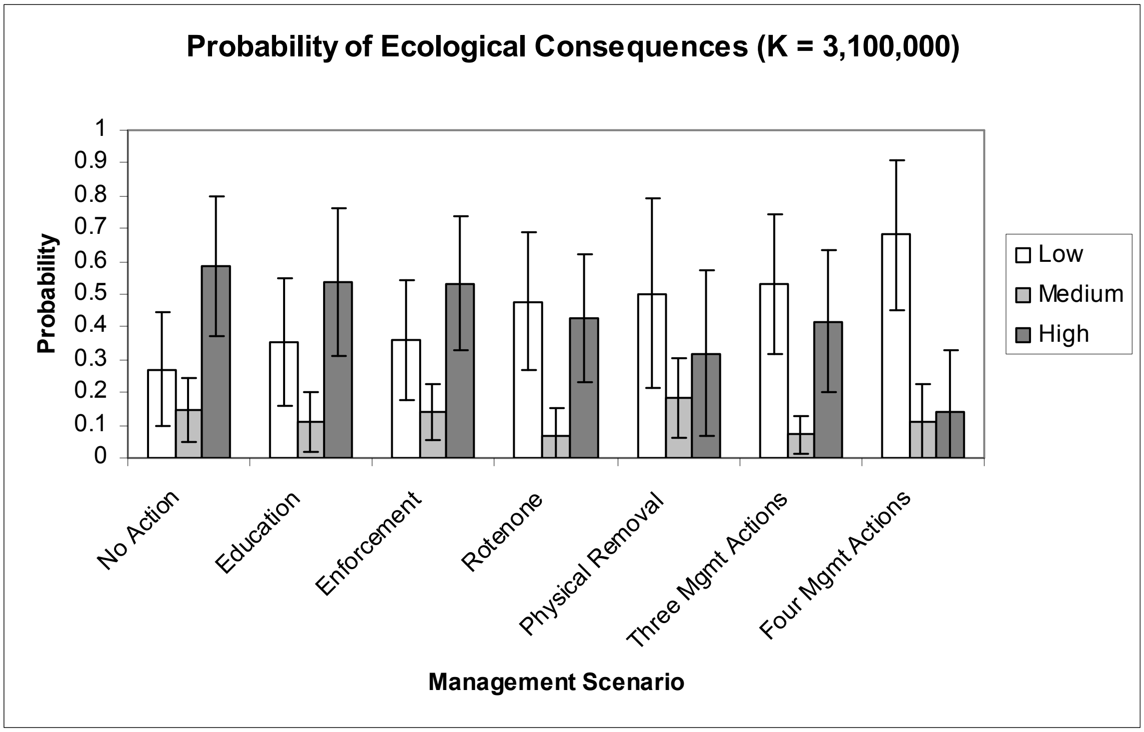


Figure 8. Same as Figure 6 except here the carrying capacity parameter for yellow perch, K, is set to 3,100,000.

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Appendix A1

Yellow Perch Risk Assessment Survey Part 1

Example Questions

The questions below are only a sample. Our survey contained similar questions for each uncertain parameter and each management scenario.

Begin filling in the **"No Action"** worksheet (see Appendix 2A below) by answering the questions below for the "probability of arrival via human introduction" (row 11). On this worksheet you will answer all questions as if the "no action" scenario described above was implemented. Each question is posed in two different ways (A and B). Please feel free to choose the questioning format you are most comfortable with and use only that one; they will both lead you to the same answer. Please note that the values you enter for the "probability of arrival via human introduction" must be between 0 and 1. **It is very important that you only enter values in yellow coloured cells.** Questions 1 and 2 will elicit the end-points of your distribution, and question 3 will elicit the median. These three points form the "backbone" of your distribution, and the rest of the questions elicit points that will provide the remaining shape of your distribution. The probability graphs for each parameter will fill in as you enter your answers, which will allow you to see the shape of the curves and make adjustments to your answers if necessary. If you wish to comment on the reasoning for your answers, space is provided to the right of the probability graphs (yellow cells R15-X26). Feel free to use more space if desired.

Question 1 (answer in cell **D11**)

A **Below** what value for the probability of arrival via human introduction do you believe there is **no way** (0 probability) that the true value will occur?

B I believe there is **no way** (0 probability) that the value for the probability of arrival via human introduction of yellow perch in Shuswap Lake in the next 5 years could be **less than** ____.

Question 2 (answer in cell **L11**)

A **Above** what value for the probability of arrival via human introduction do you believe there is **no way** (0 probability) that the true value will occur?

B I believe there is **no way** (0 probability) that the value for the probability of arrival via human introduction of yellow perch in Shuswap Lake in the next 5 years could be **greater than** ____.

Question 3 (answer in cell **H11**) – **Median**

A What value for the probability of arrival via human introduction do you believe there an equal, **50% chance** (0.5 probability) that the true value will occur **above** or **below**?

B I believe there is an equal, **50% chance** (0.5 probability) that the value for the probability of arrival via human introduction of yellow perch in Shuswap Lake in the next 5 years could be either **above** or **below** ____.

Question 4 (answer in cell **E11**)

A **Below** what value for the probability of arrival via human introduction do you believe there is a **1% chance** (0.01 probability) that the true value will occur?

B I believe there is a **1% chance** (0.01 probability) that the value for the probability of arrival via human introduction of yellow perch in Shuswap Lake in the next 5 years could be **less than** ____.

Question 5 (answer in cell **K11**)

A **Above** what value for the probability of arrival via human introduction do you believe there is a **1% chance** (0.01 probability) that the true value will occur?

B I believe there is a **1% chance** (0.01 probability) that the value for the probability of arrival via human introduction of yellow perch in Shuswap lake in the next 5 years could be **greater than** ____.

Question 6 (answer in cell **F11**)

A **Below** what value for the probability of arrival via human introduction do you believe there is a **5% chance** (0.05 probability) that the true value will occur?

B I believe that there is a **5% chance** (0.05 probability) that the value for the probability of arrival via human introduction of yellow perch in Shuswap Lake in the next 5 years could be **less than** ____.

Question 7 (answer in cell **J11**)

A **Above** what value for the probability of arrival via human introduction do you believe there is a **5% chance** (0.05 probability) that the true value will occur?

B I believe that there is a **5% chance** (0.05 probability) that the value for the probability of arrival via human introduction of yellow perch in Shuswap Lake in the next 5 years could be **greater than** ____.

Question 8 (answer in cell **G11**)

A **Below** what value for the probability of arrival via human introduction do you believe there is a **25% chance** (0.25 probability) that the true value will occur?

B I believe that there is a **25% chance** (0.25 probability) that the value for the probability of arrival via human introduction of yellow perch in Shuswap Lake in the next 5 years could be **less than** ____.

Question 9 (answer in cell **I11**)

A **Above** what value for the probability of arrival via human introduction do you believe there is a **25% chance** (0.25 probability) that the true value will occur?

B I believe that there is a **25% chance** (0.25 probability) that the value for the probability of arrival via human introduction of yellow perch in Shuswap Lake in the next 5 years could be **greater than** ____.

Appendix A2

Yellow Perch Risk Assessment Survey Part 1

Example Spreadsheet

The spreadsheets shown below are only a sample. Our survey contained similar worksheets for each uncertain parameter and each management scenario.

Appendix B

Yellow Perch Risk Assessment Survey Part 2

Example Questions

1. What type of yellow perch populations are you MOST familiar with?
    a. Native
    b. Non-native

2. How many yellow perch do you thing need to arrive in Shuswap Lake in order to successfully reproduce and establish? (i.e. what is the minimum number of yellow perch required to create an established population in Shuswap Lake?)
    a. <10
    b. 10-50
    c. 50-100
    d. >100

3. In your experience, what region(s) of the lake to ADULT yellow perch inhabit?
    a. Littoral zone
    b. Pelagic zone
    c. Both

4. If you answered b or c in question 3, what factors do you believe lead ADULT yellow perch to become pelagic rather than littoral? Multiple answers possible.
    a. Lake size (large)
    b. Lake depth (deep)
    c. Size of littoral zone (small)
    d. Low prey abundance in littoral zone
    e. High predator abundance in littoral zone
    f. Low abundance of vegetation in littoral zone
    g. High abundance of vegetation in littoral zone
    h. High temperature in littoral zone
    i. None of the above
    j. Other, please specify

5. If you answered b or c in question 3, please describe the depths at which ADULT yellow perch are most frequently found in the PELAGIC zone.
    a. <5 metres
    b. 5-10 metres
    c. 10-20 metres
    d. 20-40 metres
    e. >40 metres

6. If you answered a in question 3, please describe what factors you believe best characterize yellow perch LITTORAL habitat. Multiple answers possible.
    a. Sand
    b. Gravel/cobble
    c. Mud/silt
    d. Vegetation

   e. Woody debris
   f. None of the above
   g. Other, please specify

7. Based on your experience, if yellow perch do establish in Shuswap Lake, what region of the lake do you believe they are MOST LIKELY to inhabit?
   a. Littoral zone
   b. Pelagic zone
   c. Both

8. At what densities (fish/ha) are ADULT yellow perch typically found in the water bodies you are familiar with? Based on your experience please provide minimum, mean, and maximum estimates.

9. At what densities (fish/ha) do yellow perch populations show signs of stunting? Based on your experience, please provide minimum, mean, and maximum estimates.

10. Based on your experience, if yellow perch do establish in Shuswap Lake, what do you believe would be the carrying capacity (fish/ha) for yellow perch? Please provide minimum and maximum estimates.

11. At what densities (fish/ha) are yellow perch populations forced to spread out and establish in new areas of the lake in search of food or better habitat? Based on your experience, please provide minimum, mean, and maximum estimates.

12. In your experience do yellow perch move through less suitable habitat in search of food or better habitat?
    a. Yes
    b. No

Appendix C

Financial Report