Approval

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Abstract

I developed a quantitative risk assessment model in a Bayesian decision analysis framework to evaluate management options for the potential invasion of non-native yellow perch (***Perca flavescens***) in Shuswap Lake, British Columbia. Probability distributions of key model parameters were determined by eliciting expert opinion during a workshop and by a mail-out survey. The model produced distributions of weighted average probabilities of abundance and spatial distribution of yellow perch in the lake 10 years after introduction. I found that impacts of a yellow perch invasion on sockeye salmon would be best mitigated by undertaking a combination of actions including education, enforcement, rotenone, and physical removal. The rank order of management opt distrz44VYfmm©mgInDGmfw©7gVIaD4fmm9j4IlDGjfVmjwjI.j4I©97gjmgII©97gjmgII©Vm7m9

To all those who have inspired me
to make the world a better place

Acknowledgements

I thank Randall Peterman for his expertise, guidance, and encouragement

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Introduction

Ecosystems are composed of intricate networks of relationships among living organisms and the environment in which they live. Changes to these networks through habitat destruction, pollution, climate change, or introduction of new species can have devastating effects. In particular, invasion of non-indigenous species (NIS) is recognized by ecologists as a leading threat to global biodiversity and ecosystem functioning (Vitousek et al. 1996; Sala et al. 2000; Rosenzweig 2001; Rahel et al. 2008). Noncontrol costs of invasive species in Canada is between $13.3 and $34.5 billion CDN per year, with damages caused by AIS costing nearly $750 million CDN per year (Colautti et al. 2006a). In the United States, it is estimated that the total damage and control costs of invasive species is $137 billion USD per year (Pimentel et al. 2000). Worldwide the impact of AIS is estimated to cost more than $314 billion USD per year in damage and control costs (Pimentel et al. 2005). None of theses cost estimates include the value of losses in biodiversity or ecosystem services.

In this paper, I develop a quantitative risk assessment model for an invasive fish aquarium industry, live food fish industry, recreational boating, canals and diversions, and commercial shipping (Kerr et al. 2005; Johnson et al. 2006; Gertzen et al. 2008).

Establishment of an introduced NIS depends on its ability to survive and successfully reproduce in its new environment. Survival and reproduction depend on a variety of factors including habitat suitability, food availability and abundance, as well as predator abundance and vulnerability of introduced species to these predators (Brown 1993; Lewis and Kareiva 1993; Bartell and Nair 2003). Establishment of NIS may also be affected by the number and frequency with which individuals are introduced into the new environment (i.e., propagule pressure) and by reproductive success at extremely low densities (i.e., Allee effects) (Lewis and Kareiva 1993; Drake 2004; Leung et al. 2004; Colautti et al. 2006b; Drake and Lodge 2006; Duggan et al. 2006; Copp et al. 2007). If a NIS becomes established, it may proceed to the final stage of the invasion process, spread.

Biological invasions are often characterized by a lag phase while the population grows to fill the habitat at the introduction site, followed by a rapid expansion after the initial range is filled (Frappier et al. 2003; Rilov et al. 2004). Once a NIS has become widespread, it is often difficult to eradicate. However, populations of invasive species can still be managed, through biological, chemical, and/or physical control and containment methods, to reduce their impacts on native species and ecosystems (Wittenberg and Cock 2005; Hulme 2006; Genovesi 2007). While eradication is the complete and permanent removal of a NIS species from a defined area, control is the reduction of population density and abundance in order to keep damages at an acceptable level. Containment is aimed at limiting the spread of a NIS and containing its presence within defined

Yellow perch is a freshwater fish indigenous to North America. Although it was originally restricted to areas east of the Continen

(1977), Craig (1987), and Brown et al. (2009) provide excellent reviews of yellow perch biology.

The yellow perch risk assessment conducted by DFO was carried out across a relatively broad spatial scale and was not intended to provide detailed information or management advice for specific waterbodies or on impacts to individual populations or species (Bradford et al. 2008). My study was designed to complement work being done by both federal and provincial agencies on AIS in B.C. My objective was to provide more detailed, quantitative information for a specific water body (Shuswap Lake, near Salmon Arm, B.C.) and the potential impacts on a particular species (Pacific sockeye salmon).

In the absence of natural predators, yellow perch have been known to out-breed and out-compete native fish species, including salmonids, and can dominate smaller lake systems in just a few years (Scott and Crossman 1973; Clady 1978; Fraser 1978; Shrader 2000; Bonar et al. 2005). The concern in B.C. is with potential impacts on Pacific salmon, particularly sockeye salmon, if yellow perc

I used decision analysis, which is a formal method for explicitly and quantitatively taking uncertainties into account when evaluating management options (Walters 1986; Morgan and Henrion 1990; Peterman and Anderson 1999), as a framework for my risk assessment model. Decision analysis has been applied in fisheries management (Walters 1986; Punt and Hilborn 1997; Peters and Marmorek 2001; Peterson and Evans 2003; Patrick and Damon-Randall 2008), endangered species management (Maguire 1986; Drechsler 2000; VanderWerf et al. 2006; Pestes et al. 2008; Gregory and Long 2009), and more recently the management of invasive species (Maguire 2004, Haeseker et al. 2007).

I had two research objectives. The first was to quantify expert knowledge about (i) critical population dynamics parameters of non-native yellow perch in Shuswap Lake, (ii) ecological impacts of a potential yellow perch invasion on sockeye salmon, and (iii) management costs associated with different eradication and control actions. The second objective was to quantitatively evaluate the effectiveness at reducing ecological consequences (i.e., impact on sockeye salmon) of management actions related to controlling yellow perch at different stages of invasion. Information resulting from this risk assessment will assist with allocation of limited funds and help provincial fisheries managers choose the most appropriate control method to deal with threat of invasive yellow perch. This model could be adapted as a mana

Methods

This risk assessment model (decision analysis) for the management of invasive yellow perch in Shuswap Lake had eight components, as detailed in the next sections: (1) management objectives, (2) alternative management actions (3) uncertain states of nature, (4) probabilities of each uncertain state of nature, (5) models for predicting the outcome of each combination of management action and uncertain state of nature, (6) ranking of management actions, and (7) sensitivity analyses (Peterman and Anderson 1999). The eighth component, a decision tree, illustrates connections among these components (Figure 2).

Management Objectives

I used the following two management objectives to guide my decision analysis: (1) minimize the probability of large ecological consequences (defined below) resulting from the abundance of yellow perch in Shuswap Lake 10 years after arrival, and (2) minimize the probability of widespread spatial distribution of yellow perch in Shuswap Lake 10 years after arrival.

Management Actions

I included five alternative management actions representing a range of possible control methods for reducing the ecological impacts of invasive yellow perch in Shuswap Lake in this model. These actions were “No Action”, “Education”, “Enforcement”, “Rotenone”, and “Physical Removal”. Descriptions of these management actions can be found in Table 1. Each action was intended to control a different stage of the invasion process. For example, “Education” was intended to prevent the arrival of yellow perch in

Shuswap Lake, whereas "Physical Removal" was intended to control the establishment and spread of yellow perch after they have arrived in Shuswap Lake. By combining multiple actions, managers could attempt to control all three invasion stages in a single management option. I ranked management actions (and their combinations) to determine which one best satisfied the stated management objectives, while keeping management costs to a minimum. Estimated costs of each management action were included in the analysis to illustrate to managers trade-offs between expenditures on yellow perch control actions and probability for each of several magnitudes of ecological consequences.

Uncertain States of Nature

The uncertain states of nature included in my risk assessment model were related to the three stages of invasion: (1) arrival, (2) establishment (survival and reproduction), and (3) spread (Hengeveld 1989; Andow et al. 1990; Kolar and Lodge 2002; Mandrak and Cudmore 2006). Because data regarding invasive yellow perch in B.C. were quite limited, the input data for my risk assessment model were generated by eliciting the expert opinions of fisheries scientists and managers. For each management action, experts were asked to provide a probability distribution for each uncertain state of nature described below. The definitions of these uncertain parameters were developed in accordance with the "clarity test" (Morgan and Henrion 1990), which dictates that an uncertain quantity must be well-specified for a meaningful probability distribution to be quantified.

established population) will arrive in Shuswap Lake in the next 5 years. That minimum number was unknown and was therefore based on expert opinion (see below). The probability of arrival was further divided into “probability of arrival via human introduction” and “probability of arrival via natural dispersal”; a separate probability distribution for each of these parameters was elicited via a standardized questioning procedure that is described below.

The establishment stage was represented in the model by a population growth parameter, the “intrinsic rate of natural increase” or “intrinsic rate of population growth” (***r***). This rate may 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 adult fish in the previous year). In this case, I was interested in the intrinsic rate of population growth of yellow perch once they have arrived in Shuswap Lake.

The final stage of the invasion process, spread, was represented in the model by the “rate of spread”. This uncertain parameter was defined as the rate (kilometres per year) at which yellow perch spread throughout Shuswap Lake from their point of introduction (Figure 1), once a minimum density of yellow perch is attained. The rate of spread did not include spread via larval drift, but only the spread of adult yellow perch. The spread of larval yellow perch due to lake currents has been identified as a major dispersal vector for yellow perch in their native range (Beletsky et al. 2007), however, in this case too little was known about the specific conditions in Shuswap Lake for experts to have included this transport process in their estimates of the spread rate.

Elicitation of Expert Opinion

Workshop

In July 2008, I held a workshop in Kamloops, B.C., involving federal and provincial fisheries scientists and managers who work on management of sockeye salmon and/or invasive yellow perch in the Thompson region procedures and potential biases, current distribution of yellow perch in B.C., as well as physical and biological characteristics of Shuswap Lake (because most survey participants were not familiar with the lake).

The first part of the survey was designed to elicit probability distributions for each uncertain parameter under each management action. A Bayesian view of probability was used in which the probability of some parameter value was defined 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). Using the fixed probability

calculated the expected (weighted average) probabil

this case 10 years. Because spread often begins only after the habitat occupied by the habitat as the entire surface area of the lake (i.e., 310 km^2; the littoral zone accounts for less than 12 % of the total surface area). I modelled this scenario only, and I did not model a scenario in which yellow perch restricted themselves to the littoral zone. For this reason, I converted the linear spread distance of yellow perch into the surface area (measured in kilometres squared) inhabited by yellow perch 10 years after arrival.

biomass of juvenile sockeye salmon. Thus, the biomass of yellow perch that could be supported by Shuswap Lake could be the same as the total biomass of juvenile sockeye salmon produced by the lake if there were no sockeye. Note that this also assumes that the yellow perch population will rely solely on the pelagic productivity of Shuswap Lake. Based on Shuswap Lake's productivity, as estimated by Shortreed et al. (2001), the PR model can estimate the biomass of juvenile sockeye salmon (smolts) that the lake can sustain. The first step was to estimate the maximum number of sockeye smolts produced by Shuswap Lake each year:

(4) $$SN_{MAX} = PR_{units} (SD_{MAX}) ,$$

where SN_{MAX} is the maximum annual smolt capacity for Shuswap Lake measured in number of fish, PR_{units} is the number of PR units in Shuswap Lake, and SD_{MAX} is maximum density of smolts measured in number of fish per PR unit. There are 4098 PR units in Shuswap Lake (Hume et al. 1996) and SD_{MAX} has been observed to be 23,000 smolts per PR unit (Koenings and Burkett 1987). The next step was to convert maximum smolt capacity into maximum smolt biomass:

(5) $$SB_{MAX} = SN_{MAX}(W_{MAX}) ,$$

where SB_{MAX} is the maximum annual smolt biomass measured in grams per year, and W_{MAX} is the average weight per smolt in Shuswap Lake measured in grams. For this where K is the carrying capacity of yellow perch in Shuswap Lake measured in number of fish, and W where S_R is the number of adult sockeye salmon population produced by Shuswap Lake when the abundance of yellow perch in the lake is equal to K_{ACT}, measured in number of fish. P is the percent reduction in the adult sockeye salmon population as a result of specific yellow perch abundance (K_{ACT}) in Shuswap Lake. It was not necessary to include uncertainty in these PR model calculations because any uncertainty in the predicted baseline K value would not have influenced results of this analysis (see results of sensitivity analysis below).

Performance Measures

The overall impact of an invasive species is related to its abundance as well as its total area occupied (Parker et al. 1999). In my case, the impact or “ecological consequences” of a yellow perch invasion in Shuswap

because they actually represent a large number of adult sockeye salmon and thus potentially large economic and ecological losses. For example, a 5 percent reduction in abundance would represent 500,000 adult sockeye in years when Fraser River sockeye returns are 10 million. The workshop participants also provided feedback on Part 1 of the survey (Appendix A), and identified a number of quesptions that were subsequent l z7©mm54w©97gVIrr

I received eleven written responses to Part 2 of the survey, only two of which were from fisheries scientists and managers familiar with non-native yellow perch populations in their introduced range; the rest of the respondents work in the native range. Key results from Part 2 are summarized in Table 3. In Part 2 of the survey, experts provided estimates of the initial number of yellow perch (N estimates ranging from 10,000 to 22,000 fish (Table 3). I again drew upon this range of estimates to inform my sensitivity analysis.

Survey participants were split on their views regarding whether yellow perch would inhabit the littoral and/or pelagic zone of Shuswap Lake. Four out of eleven experts believed that adult yellow perch would inhabit both littoral and pelagic zones, while the other seven experts believed adult yellow perch would be limited to the littoral

Actions” option, that best achieves the reduction of ecological consequences resulting

The two combinations of management actions that were explored had higher financial costs than the previously described options (Table 6). The combination of “Education”, “Enforcement”, and “Rotenone” was estimated to cost between $680,000 and $930,000 per year for the first 4 years, after which time, the cost would decrease to between $300,000 and $550,000 per year. The final management action, a combination of n, “ 0tth, n”t50n”0,000 andgIcD4fmm9j4IoDGmfwar©97gVIsDGgf©Y©m9ItDGjfVmjw©9Yw9I,DGmf7 baseline K value, the results are again quantitatively similar to the original analysis, and the rank order of actions is identical to the baseline case (Table 7).

Median Probability of Yellow Perch Spatial Distribution

I investigated the spatial distribution of yellow perch in Shuswap Lake using two alternative points of introduction (Points B and C), in addition to the baseline point of introduction (Point A) identified by workshop participants (Figure 1). Results indicate that the point of introduction used in the spread model does not alter the outcome of the risk assessment model and does not alter the rank order of management actions (Table 7). The median probability across all experts of widespread, moderate, localized, and no spread so ed mfeve ribctiIrDjf4V94g7IhDGgmfwV©9IeD4fmm©mgI DGmfVw74gIRDG7fjwm7jIeGjf

5,000 (Figure 4), while the median probability of widespread distribution calculated using a lag-density of 10,000 (Figure 7B) is slightly lower. Despite these changes in the probability of different spatial distributions, the changes were small and the rank order of management actions is about identical to the baseline analyi7ITgfgI4fDjV©V©g7IoDGmf79VjmgIbDGy increases the median probability of no spread to over twice that of the “No Action” option.

The poor performance of the “Education” and “Enforcement” management actions indicates that experts believe that either these actions would be ineffective at reducing the human introduction of yellow perch into Shuswap Lake or that the human introduction of yellow perch does not represent a significant threat and thus preventing it would not change the probability of ecological consequences. This belief is embedded in the expert survey responses and thus reflected in [illegible]

fisheries scientists and managers with extensive knowledge of yellow perch would still be very uncertain as to how yellow perch would behave when introduced into this B.C. lake.

From a methodological perspective, the wide range of responses could also signify the presence of bias, either cognitive or motivational. When conducting expert elicitation, it is important to be aware of potenti

Experts were divided in their belief about whether yellow perch would inhabit the pelagic zone of Shuswap Lake. According to the experts, the most likely factors that would lead yellow perch to become pelagic are higher prey abundances and fewer predators in the pelagic zone, as well as high temperatures in the littoral zone. Experts also believe that yellow perch may become pelagic as a result of high population density;

background information and the survey instructions

Model results also indicate that once yellow perch arrive in Shuswap Lake, preventing them from spreading throughout the lake might be somewhat difficult. This is indicated by the very low probabilities of localized and moderate spread compared to the much higher probabilities of widespread spatial distribution across all management actions. It appears that management actions such as the "Four Management Actions" option, increase the probability that yellow perch will not spread throughout the lake, presumably by controlling their abundance to the point that the population is unable to surpass the lag-density within the 10 year time period. However, if yellow perch do surpass the lag-density and begin to disperse, it is more probable that they will become widespread throughout the lake than remain localized. This is due to the rather high rates of spread elicited from experts, and the belief that "Physical Removal" will not necessarily be successful at containing a yellow perch population in Shuswap Lake.

Although piscicides such as rotenone are the most successful means of eradicating invasive freshwater fishes, if applied to Shuswap Lake, rotenone would have devastating impacts on important native fish species including sockeye salmon, because it is not a individual can require significant efforts and resources. Larger water bodies with more widespread distribution of invasive fish will require more effort for eradication than a smaller lake with more localized distribution of invasive fish. Regardless of the size of the water body, eradication efforts will be most successful if they are started in the early stages of invasion, when the population is smaller and more localized. When control activities are delayed, eradication often becomes infeasible, if not impossible. If eradication is not feasible, management of the AIS by controlling its population and attempting to slow or halt its geographic spread may be the only other option. Thus, based on the results of this analysis, complete eradication of yellow perch from Shuswap Lake does not appear likely, but physical removal efforts to control and contain yellow perch may be effective at reducing the ecological consequences of invasion. Physical removal efforts do have the potential to affect non-target species, and thus careful consideration should be given to the potential “by-catch” of different removal methods when planning eradication of yellow perch in Shuswap Lake.

Eradications are often viewed as extremely costly endeavours, and indeed many such campaigns have required huge monetary resources, e.g., Lake Davis, California (Julie Cunningham, California Department of Fish and Game, Portola, California, personal communication). One of the problems in assessing how much eradications will cost is that the available literature often does not report such data, and results of removal projects carried out in the early stages of invasions are often not published at all. Trade-offs exist between costs of erais isi ao Y©m9IiDGjfVmjwjI eradications. This is the reason I have included estimates for the cost of each management action in this analysis, to help managers make decisions about which actions to take, and when to start. By comparing the costs of management actions and their effectiveness at reducing high ecological consequences of yellow perch invasion, managers should be better prepared to make decision about what action to take. It is estimated that the “Physical Removal” action could cost between $250,000 and $500,000 CDN every year until yellow perch are eradicated from the Shuswap Lake. If eradication of yellow perch is not possible, these efforts might need to continue indefinitely to control the abundance and spread of yellow perch, or at least as long as those efforts are effective at mitigating the impacts of invasive yellow perch on sockeye salmon. The highest ranked management scenario, the “Four Management Actions” option, which includes “Physical Removal”, is estimated to cost between $925,000 and $1,425,000 CDN per year, but is significantly better at reducing the median probability of high ecological consequences.

Update

When the survey was distributed in August 2008, the populations of yellow perch most closely connected to Shuswap Lake were in Hiuihill and Sinmax Creeks (Runciman and Leaf 2008). In early September 2008, MOE confirmed the presence of yellow perch in Adams Lake, a major sockeye salmon producing lake directly connected to Shuswap Lake via the Adams River. Six yellow perch were caught in Adams Lake in 2008 and five more perch have been caught in the lake as of July 2009. All yellow perch were found approximately 10 km south of Squaam Bay/outlet of Sinmax Creek. Although I can only speculate how this information may have changed the survey responses, it is very possible that experts would have had a higher degree of belief in higher estimates for the probability of arrival via natural dispersa

Shuswap Lake. Thus, a good estimate of this parameter by undertaking sampling would provide managers with more accurate predictions of yellow perch abundance if they arrive in Shuswap Lake, and thus more accurate predictions of the potential impacts on sockeye salmon even if uncertainty about this parameter did not affect the rank order of management options.

Data collected from Adams Lake is being used to estimate the age structure of an invasive yellow perch population, which will also help estimate the intrinsic rate of increase if the number of new recruits to the yellow perch population could be determined each year. Recruitment in yellow perch is known to be quite variable and from Adams Lake into Shuswap Lake. Due to the presence of juvenile sockeye salmon in Adams Lake, rotenone is not a realistic method to employ in this situation, and the physical removal of yellow perch is likely the only feasible methods for control and containment in this situation. This scenario was not included in my analysis because at the time there were no yellow perch populations upstream from Shuswap Lake that could not feasibly be eradicated using rotenone. In this analysis, physical removal was only considered as a management action to deal with yellow perch once they arrived in Shuswap Lake, not to prevent their arrival in Shuswap Lake.

Sampling in Adams Lake will also provide fisheries managers with the opportunity to track the rate of spread of yellow perch and experiment with different methods to physically remove yellow perch. Experimental control and containment activities aimed at preventing a yellow perch population explosion in Adams Lake would indicate the most effective physical removal methods and what amount of effort and financial support would be needed to eradicate yellow perch, or at a minimum keep population levels low. This information would be very useful if and when yellow perch make their way into Shuswap Lake, and control and containment activities become necessary. Long-term sampling in Adams Lake will also provide an index of abundance and measure the relative effectiveness of proposed control and containment efforts. These should also be investigated. Finally, my analysis encourages continued sampling in Shuswap Lake to monitor the presence of yellow perch, so that physical removal efforts can begin immediately upon their discovery in the lake.

Although including the cost of various management actions in this analysis is one step in the right direction, a more comprehensive economic assessment of this situation would, in particular, assess the cost of reduced salmon populations. This step would also assist managers in making decisions about what action to take, and when to begin. This type of economic information would be beneficial in order to put an economic value on the different impact categories. For example, if the cost of a 5% proportional reduction in the abundance of adult sockeye salmon produced by Shuswap Lake could be defined, it could be compared to the cost of the various management actions. The probability of each management action reducing high impacts could also be considered, and managers would thereby be better prepared/have more information to use when making decisions about which action to take. They would also be able to better determine whether the additional cost of one action over another is worthwhile in terms of the additional reduction in the impact on sockeye salmon.

Future research should also focus on modelling the complex interactions between yellow perch and salmon through food web, bioenergetics, and/or predator-prey models. Ecological niche modelling at the lake level could also give more predictive information about habitat use of yellow perch in Shuswap Lake, as would a spread model based on habitat characteristics.

In 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, yet ranking of management options is still possible. Equally important is the ability of decision analysis to stimulate discussion and clarify 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 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 used as inputs 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.

Tables

Table 1

Table 3. A summary of key results from Part 2 of the Yellow Perch Risk Assessment Survey. Population type refers to the type of yellow perch population, native or non-native, that experts were most familiar with. Estimates of N_0 (the starting value for the logistic growth model measured in number of fish) indicate the minimum number of yellow perch required to create an established population in Shuswap Lake. Minimum and maximum estimates of K (the carrying capacity for yellow perch in Shuswap Lake measured in number of fish) were used to inform sensitivity ana

Expert	Population type	N_0	K		Lag-density		Littoral (L) and/or pelagic (P)	Depth (m)
			Min	Max	Min	Max		
1	native	> 100	31,000	620,000	500	10,000	L and P	20-40
2	native	50-100					L	5-10
3	native	50-100	775,000	3,100,000			L	5-10
4	native	10-50					L and P	5-10
5	native	10-50					L and P	5-10
6	native	50-100	744,000	7,440,000	17,000	22,000	L	5-10
7	native	10-50	62,000	155,000	12,500	19,500	L	5-10
8	native	< 10	3,100,000	15,500,000			L	10-20
9	native	10-50					L and P	< 5
10	non-native	10-50					L	10-20
11	non-native	< 10					L	< 5

Table 4. The starting values (N_0) used in the logistic growth model for a given expert.

Table 5. The surface area of Shuswap Lake inhabited by yellow perch 10 years after arrival that would lead to localized, moderate, and widespread spatial distribution as defined by the proportion of suitable habitat (per cent of the total surface area of Shuswap Lake) inhabited by yellow perch 10 years after arrival. These categories of spatial distribution were defined by workshop participants, as were the most likely points of introduction (Figure 1). The spread distance for each distribution category is the linear distance from the point of introduction (Point A, B, or C) that yellow perch will have spread 10 years after arrival as calculated by the spread model.

Category of spatial distribution	Surface area (km^2)	Percentage of suitable habitat	Point of introduction (Figure 1)	Spread distance (km)
No spread	0	0	A	0
			B	0
			C	0
Localized spread	< 78	< 25 %	A	< 27
			B	< 30
			C	< 19
Moderate spread	78 – 155	25 – 50 %	A	27-50
			B	30-54
			C	19-31
Widespread	> 155	> 50 %	A	> 50
			B	> 54
			C	> 31

Table 6. The median probability (across all experts) of high, moderate, and low ecological consequences resulting from a yellow perch invasion in Shuswap Lake under different management actions and the associated management costs and duration of each action as identified by experts at the workshop. The median probability of no impact on sockeye salmon is also included. Detailed descriptions of these management actions can be found in Appendix A.

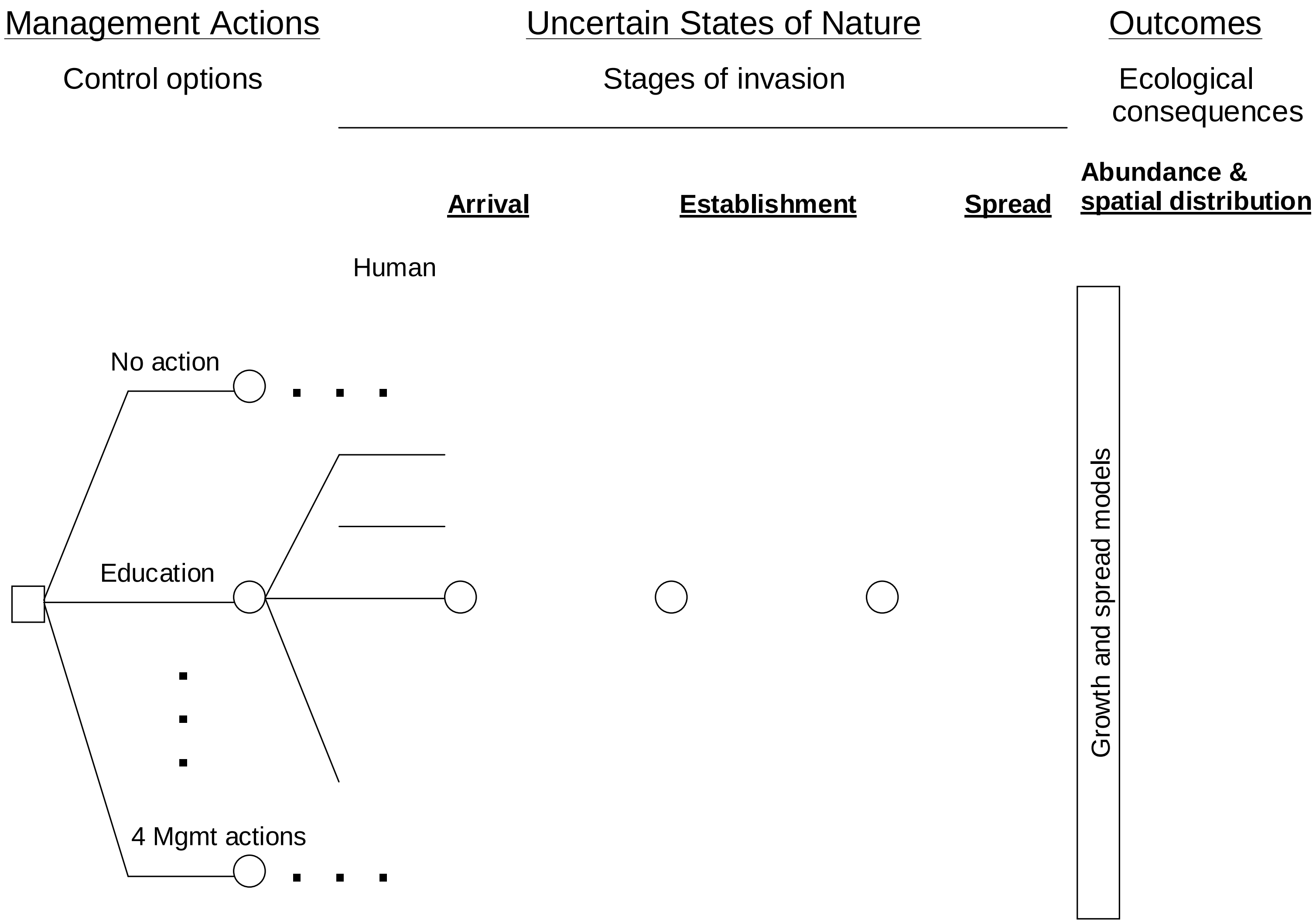
Table 7. Rank order of management actions, by case, based on results shown in Figures 3 through 7. Management actions are ranked (1 is best; 7 is worst) according to probability of high ecological consequences and widespread spatial distribution, i.e., the action ranked 1 has the lowest probability of high ecological consequences and widespread distribution, whereas the action ranked 7 has the highest probability of high ecological consequences and widespread distribution. Note: all cases are the same as the baseline parameter values and assumptions except for the item noted. Identical rankings and decimals in a column indicate ties, and ranks are averaged.

Ranking criterion:	Ecological consequences			Spatial distribution				
Case: / Mgmt actions:	Baseline K = 1,380,000	K = 775,000	K = 3,100,000	Baseline Point A	Point B	Point C	Lag-density = 2,500	Lag-density = 10,000
No Action	7	7	6	7	6.5	6.5	7	7
Education	6	6	6	5	5	5	5	5
Enforcement	5	5	6	6	6.5	6.5	6	6
Rotenone	4	4	4	3	3	3	3	3.5
Physical Removal	2	2	2	4	4	4	4	3.5
Three Mgmt Actions	3	3	3	2	2	2	2	2
Four Mgmt Actions	1	1	1	1	1	1	1	1
See Figure:	3	5A	5B	4	6A	6B	7A	7B

Figure 1. Map of Shuswap Lake, B.C., showing the most likely points of introduction for


Seymour R.
Lake
Seymour Arm
Anstey
Salmon Arm
Mara Lake
10 km

Figure 2. Decision tree illustrating the conceptual framework of this analysis. Branches radiating from the square node represent different management actions that could be taken to control the invasion of yellow perch in Shuswap Lake, whereas branches radiating from round nodes represent uncertain states of nature. For each management action, there is an uncertainty node that has a branch for every possible state of nature (combination of uncertain parameters of the growth and spread models). States of nature include arrival via human introduction (AH), arrival via natural dispersal (AN), the intrinsic rate of increase (***r***), and the rate of spread (C). The relative weighting (or probability, Pr_n) on each uncertain state of nature is the 7Y©m9I DGmf7Vw74gItDGjfVmjwjIhDGmfw


Management Actions
Control options
Uncertain States of Nature
Stages of invasion
Outcomes
Ecological consequences
Arrival
Establishment
Spread
Abundance & spatial distribution
Human
No action
Education
4 Mgmt actions
Growth and spread models

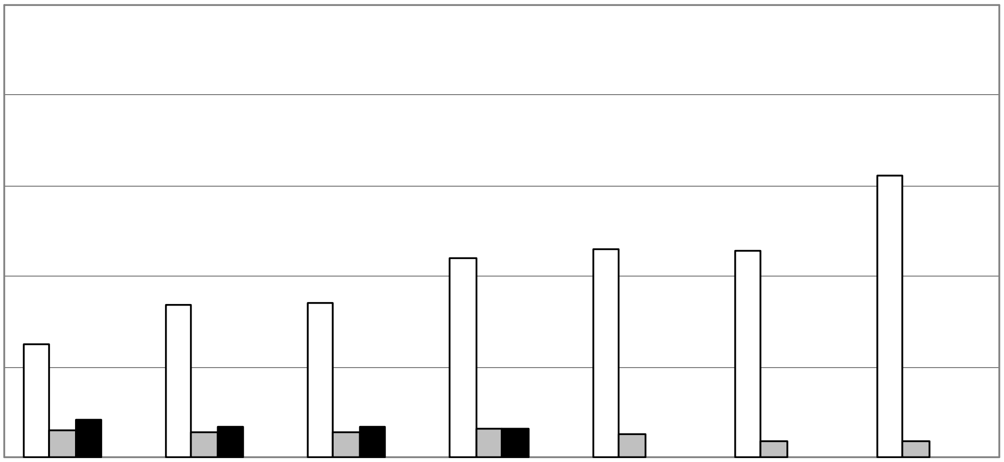


Figure 5. The median probability (across all experts) of high, moderate, low, and no ecological consequences ba

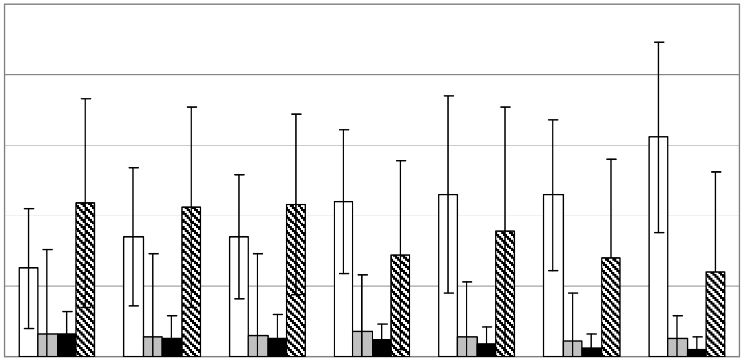


Figure 6. Results for the baseline parameter values of the model. The median probability (across all experts) of widespread, moderate, and localized spatial distribution of yellow perch in Shuswap Lake 10 years after arrival resulting from the spread of yellow perch from their initial point on introduction, in this case Point B (A) and Point C (B). Error bars represent ± one standard deviation.

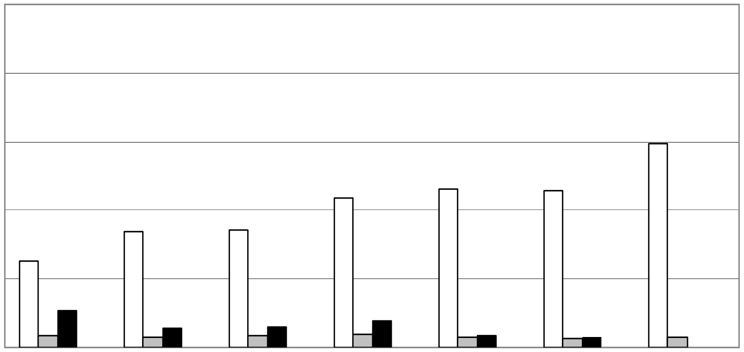


Figure 7. The median probability (across all experts) of widespread, moderate, and localized spatial distribution of yellow perch in Shuswap Lake 10 years after arrival resulting from the spread of yellow perch from their initial point of introduction, in this case Point A (Figure 1). Unlike Figure 4, which was based on the baseline value of the lag-density of 5,000 yellow perch, here I used 2,500 (A) and 10,000 (B) fish for the lag-density in the spread model. Error bars represent ± one standard deviation.

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Appendices

Appendix A. Yellow Perch Risk Assessment Survey Part 1

Questions

Step 1: Please read the background information document, "A quantitative risk-assessment model for invasive yellow perch and Shuswap Lake, British Columbia"

Step 2: Once you have read the background document, open the Excel file named **“Yellow Perch Risk Assessment Survey Part 1”** and save the file with your last name listed at the beginning of the filename.

Step 3: Fill in the worksheet labelled **“Participant Info”**. Then click on the tab for the worksheet labelled **“No Action”**. There is one tab for each management action, and we are asking you to work through one tab at a time.

No Action Scenario:
In this scenario, no action would be taken by provincial fisheries managers to prevent yellow perch from entering Shuswap Lake (arrival). If yellow perch do make their way into Shuswap Lake (by natural dispersion or human introduction), no action would be taken by fisheries managers to control their abundance (survival and reproduction) or their distribution throughout the lake (spread). 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. In this management scenario, the enforcement of fish introduction and transfer regulations by provincial conservation and fishery officers would continue as usual, but would not be increased. In practice, this means that there are still many possibilities for human to purposefully and illegally introduce yellow perch to various lakes.

Step 4: Begin filling in the “No Action” worksheet 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.

Remember to only enter value in yellow coloured cells.

Probability of Arrival via Human Introduction

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 ____**.

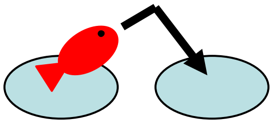
Question 9 (answer in cell **I11**)

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 ____**.

Step 5: Continue filling in the "**No Action**" worksheet by answering the questions be

Remember to only enter values in yellow coloured cells.



Probability of Arrival via Natural Dispersal

Question 1 (answer in cell **D13**)

A **Below** what value for the probability of arrival via natural dispersal 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 natural dispersal of yellow perch in Shuswap Lake in the next 5 years could be **less than ____**.

Question 2 (answer in cell **L13**)

A **Above** what value for the probability of arrival via natural dispersal 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 natural dispersal of yellow perch in Shuswap Lake in the next 5 years could be **greater than ____**.

Question 3 (answer in cell **H13**) – **Median**

A What value for the probability of arrival via natural dispersal 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 natural dispersal of yellow perch in Shuswap Lake in the next 5 years could be either **above** or **below ____**.

Question 4 (answer in cell **E13**)

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

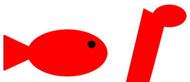
B I believe there is a **1% chance** (0.01 probability) that the value for the probability of arrival via natural dispersal of yellow perch in Shuswap Lake in the next 5 years could be **less than ____**.

Question 5 (answer in cell **K13**)

A **Above** what value for the probability of arrival via natural dispersal 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 natural dispersal of yellow perch in Shuswap lake in the next 5 years could be **greater than ____**.

Remember to only enter values in yellow coloured cells.



Intrinsic Rate of Increase

Question 1 (answer in cell **D47**)

A **Below** what value for the intrinsic rate of increase for yellow perch in Shuswap Lake 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 intrinsic rate of increase for yellow perch in Shuswap Lake could be **less than** ____.

Question 2 (answer in cell **L47**)

[illegible] **Above** what value for the intrinsic rate of increase for yellow perch in Shuswap Lake do you believe there is **no way** (0 probability) that the true value will occur?

B I believe there is **no way** (zero probability) that the value for the intrinsic rate of increase for yellow perch in Shuswap Lake could be **greater than** ____.

Question 3 (answer in cell **H47**) – **Median**

A What value for the intrinsic rate of increase for yellow perch in Shuswap Lake 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 intrinsic rate of increase for yellow perch in Shuswap Lake could be either **above** or **below** ____.

Question 4 (answer in cell **E47**)

A **Below** what value for the intrinsic rate of increase for yellow perch in Shuswap Lake do you believe there is a **1% chance** (0.01 probability) that the true value will occur?

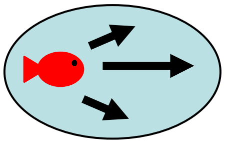
B I believe there is a **1% chance** (0.01 probability) that the value for the intrinsic rate of increase for yellow perch in Shuswap Lake could be **less than** ____.

Question 5 (answer in cell **K47**)

A **Above** what value for the intrinsic rate of increase for yellow perch in Shuswap Lake 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 intrinsic rate of increase for yellow perch in Shuswap Lake could be **greater than** ____.

Remember to only enter values in yellow coloured cells.



Rate of Spread

Question 1 (answer in cell **D83**)

A **Below** what value for the rate of spread 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 rate of spread of yellow perch throughout Shuswap Lake could be **less than ____**.

Question 2 (answer in cell **L83**)

A **Above** what value for rate of spread 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 rate of spread of yellow perch throughout Shuswap Lake could be **greater than ____**.

Question 3 (answer in cell **H83**) – **Median**

A What value for the rate of spread 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 rate of spread of yellow perch throughout Shuswap Lake could be either **above** or **below ____**.

Question 4 (answer in cell **E83**)

A **Below** what value for the rate of spread 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 rate of spread of yellow perch throughout Shuswap Lake in the next 5 years could be **less than ____**.

Question 5 (answer in cell **K83**)

A **Above** what value for the rate of spread 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 rate of spread of yellow perch throughout Shuswap Lake could be **greater than ____**.

Question 6 (answer in cell **F83**)

A **Below** what value for the rate of spread 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 rate of spread of yellow perch throughout Shuswap Lake in the next 5 years could be **less than ____**.

Question 7 (answer in cell **J83**)

A **Above** what value for the rate of spread 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 rate of spread of yellow perch throughout Shuswap Lake could be **greater than ____**.

Question 8 (answer in cell **G83**)

A **Below** what value for the rate of spread 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 rate of spread of yellow perch throughout Shuswap Lake could be **less than ____**.

Question 9 (answer in cell **I83**)

A **Above** what value for the rate of spread 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 rate of spread of yellow perch throughout Shuswap Lake could be **greater than ____**.

You have now completed all the questions related to the "No Action" management scenario. Next you will answer the SAME questions for the "Education" scenario (described below). Steps 8-13 will be much faster and easier than steps 4-7 for the "No Action" case because you will essentially be asking yourself, "How different will my answers be if I consider taking action X?"

Education Scenario:

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 (arrival). Fisheries managers would explain the consequences of invasive species introductions, and the impacts that a yellow perch invasion could have on the biological resources of Shuswap Lake. This education program would attempt to reach as many members of the public as possible, while focusing its efforts on those most likely to accidentally or intentionally introduce yellow perch into Shuswap Lake (e.g. recreational anglers). Education and awareness could include such things as town meetings, school

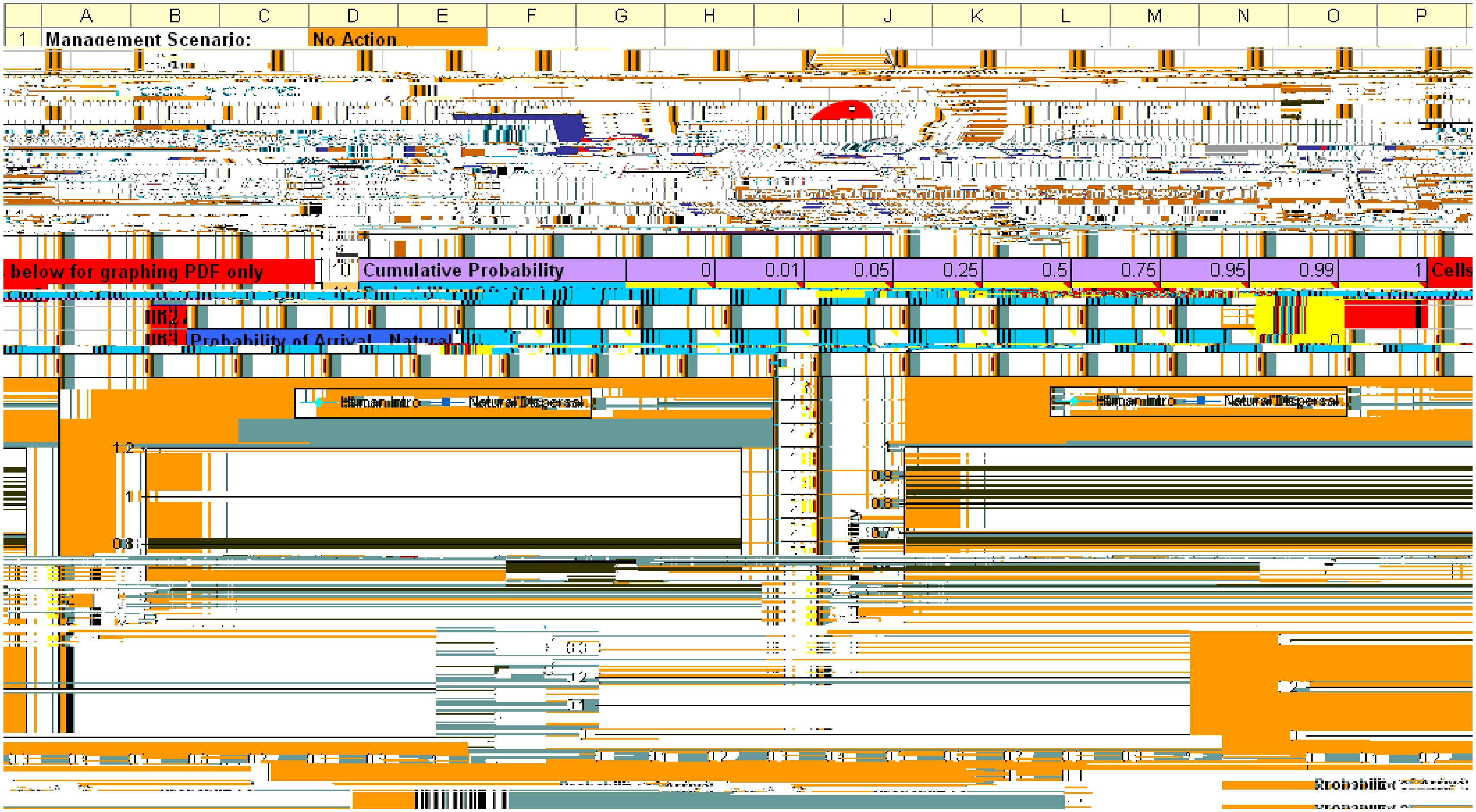
Physical Removal:
In this scenario, no action would be taken by provincial fisheries managers to prevent yellow perch from entering Shuswap Lake (arrival). If yellow perch do make their way into Shuswap Lake (by natural dispersion or human introduction) fisheries managers would physically remove perch from the lake using gillnets (or other mechanical methods such as purse seines or traps). Physical removal is unlikely to eradicate yellow perch from Shuswap Lake, even if efforts begin as soon as yellow perch are first observed in the lake. Thus, physical removal will simply attempt to control the abundance (survival and reproduction) and distribution (spread) of yellow perch in Shuswap Lake. Physical removal would take place annually, preferably before yellow perch spawn in the spring. In this management scenario, the enforcement of fish introduction and transfer regulations by provincial conservation and fishery officers would continue as usual, but would not be increased.

Step 11: Now move on to the next management scenario by clicking on the tab labelled **“Physical Removal”.** Fill in the worksheet by answering the questions listed above in Steps 4, 5, 6, and 7. On this worksheet you will answer all questions as if the “Physical Removal” scenario described above was implemented. You will notice that the probability distributions you specified for the “No Action” scenario will appear on the probability graphs for each parameter (and your numerical values will appear in the cells below your yellow answer cells). These points are provided as a reference so you can think about how physical removal may change your numerical answers compared to the baseline “No

“Three Mgmt Actions” case will be a combination of

Appendix B. Yellow Perch Risk Assessment Survey Part 1

Response Template Sheet 1: Probability of Arrival



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Management Scenario:			No Action												

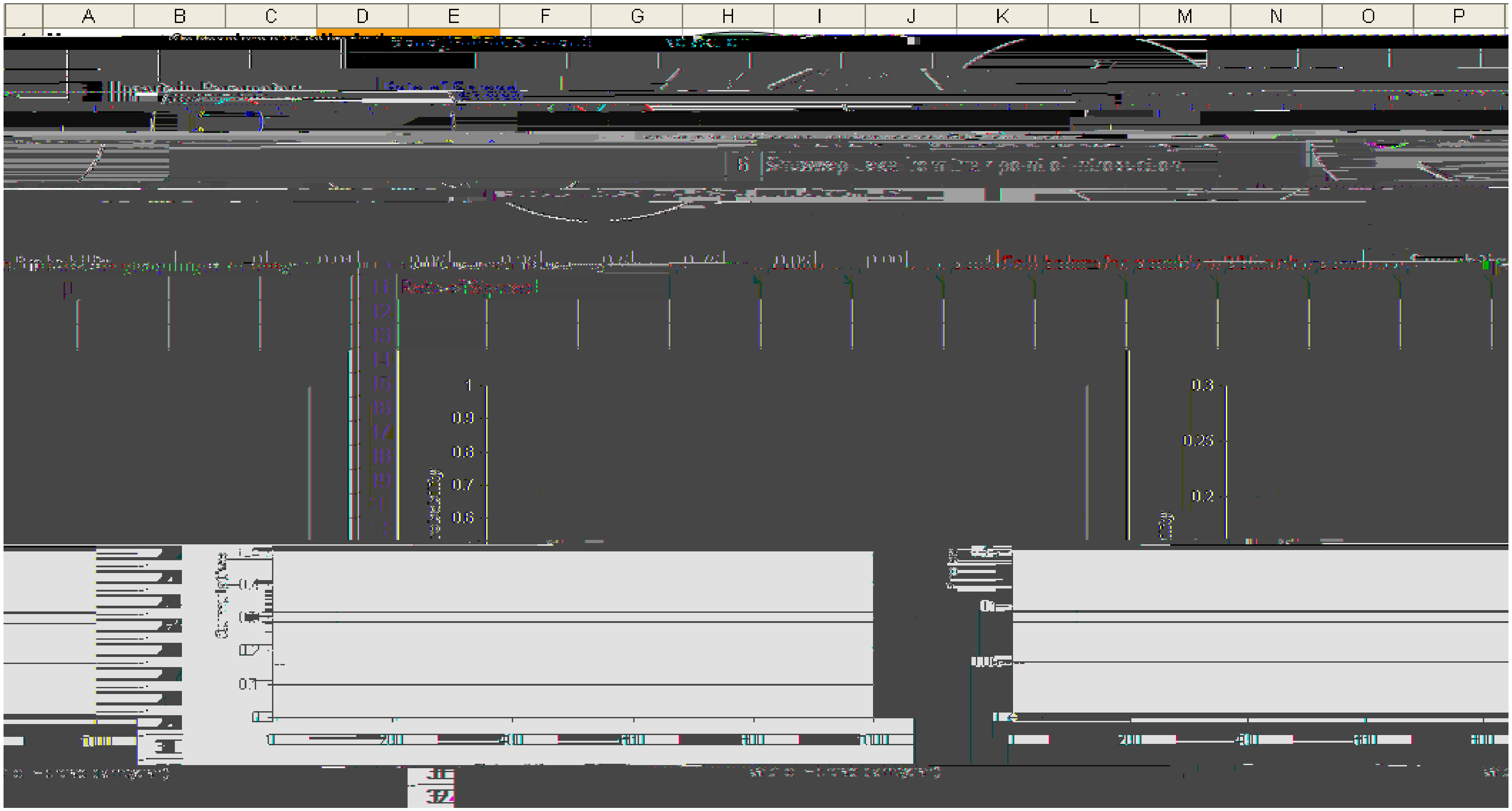
below for graphing PDF only

Cumulative Probability	0	0.01	0.05	0.25	0.5	0.75	0.95	0.99	1

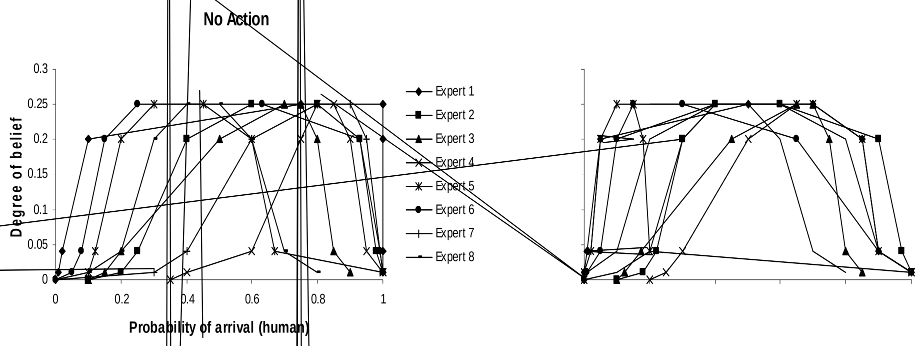
Cells

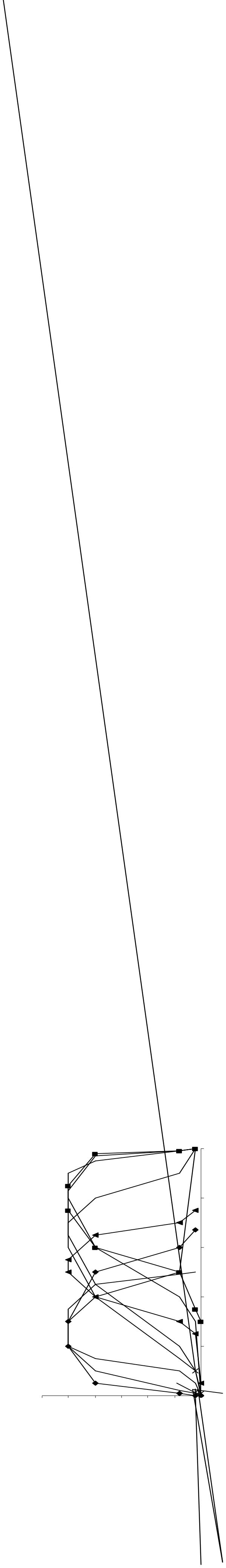
Probability of Arrival - Natural

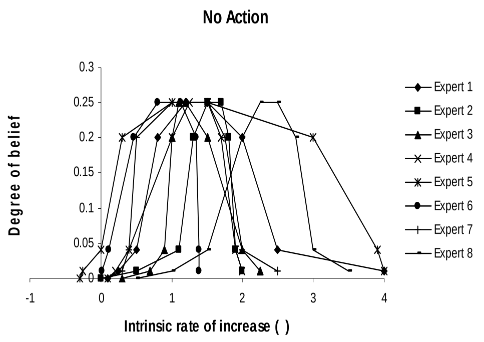
Response Template Sheet 3: Rate of Spread



Appendix C. Yellow Perch Risk Assessment Survey Part 1


No Action
Degree of belief
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
Probability of arrival (human)
Expert 1
Expert 2
Expert 3
Expert 4
Expert 5
Expert 6
Expert 7
Expert 8

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Degree of belief
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0.2
0.15
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1
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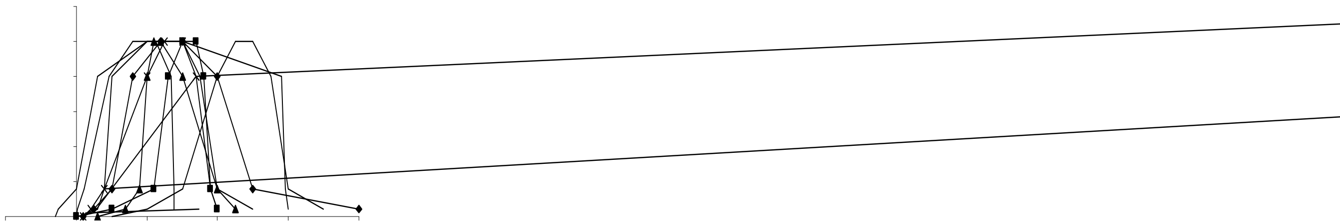
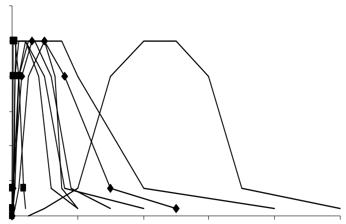
Intrinsic rate of increase ( )
Expert 1
Expert 2
Expert 3
Expert 4
Expert 5
Expert 6
Expert 7
Expert 8





Appendix D. Yellow Perch Risk Assessment Survey Part 2

Questions

6. If you answered B or C in question 4, please describe the depths at which 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

7. If you answered A in question 4, 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

8.

12. 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 estimates of:

    a. Minimum density
    b. Maximum density

13. At what densities (fish/ha) do yellow perch population show signs of stunting? Based on your experience, please provide estimates of:

    a. Minimum density
    b. Maximum density

14. 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 estimates of:

    a. Minimum density
    b. Maximum density

15. 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 estimates of:

    a. Minimum density
    b. Maximum density

16. In your experience, do yellow perch move through less suitable habitat and/or pelagic habitat in search of food of better habitat? If no, please explain.

    a. Yes
    b. No

17. In the water bodies containing NON-NATIVE yellow perch that you are familiar

19. By what means did yellow perch displace the fish species listed above? Multiple answered possible.

    a. Competition for food
    b. Competition for habitat
    c. Predation
    d. None of the above
    e. Other, please specify

20. In your experience, what control measures have been used by fisheries managers to eradicate or control invasive fish species?

21. Have any of the control measures listed above been used to eradicate or control NON-NATIVE yellow perch populations in the water bodies you are familiar with? If yes, please specify which control measures have been used.

    a. Yes
    b. No

22. Have any of the control measures listed above been successful at eradicating or controlling NON-NATIVE yellow perch populations? If yes, please specify which control measures have been used.

    a. Yes
    b. No

23. In your experience, how much management actions aimed at eradicating or controlling invasive fish species cost? Please provide cost estimates of the Yes following management actions th©mgIsDGgf©Y9jYIiDGjfVm7g7IvDGmfw©IsDGgf©Y9jYIiD oeIaD4fmm9j4InDGmfw©VIrDjf4V94VI DGmf5Gg4fY5' d z [IdDGmfw©97gVI.Dj©m] '<zd–

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25. In your experience, what abundance of yellow perch in Shuswap Lake do you believe would lead to MODERATE ecological consequences as defined above?

    a. 10-20 fish/ha
    b. 20-30 fish/ha
    c. 30-40 fish/ha
    d. 40-50 fish/ha
    e. 50-100 fish/ha
    f. 100-500 fish/ha
    g. 500-1000 fish/ha

26. In your experience, what abundance of yellow perch in Shuswap Lake do you believe would lead to HIGH ecological consequences as defined above?

    a. >50 fish/ha
    b. >100 fish/ha
    c. >250 fish/ha
    d. >500 fish/ha
    e. >750 fish/ha
    f. >1000 fish/ha
    g. >5000 fish/ha

27. If spatial distribution is measured as the proportion of LITTORAL habitat occupied by yellow perch, what spatial distribution of yellow perch in the do you believe would lead to LOW ecological consequences as defined above?

    a. <10%
    b. 10-15%
    c. 15-20%
    d. 20-25%
    e. 25-35%
    f. 35-50%
    g. 50-60%
    h. 60-75%
    i. 75-80%
    j. >80%

28. If spatial distribution is measured as the proportion of LITTORAL habitat occupied by yellow perch, what spatial distribution of yellow perch in the do you believe would lead to MODERATE ecological consequences as defined above?

    a. <10%
    b. 10-15%
    c. 15-20%
    d. 20-25%

f. 35-50%
g. 50-60%
h. 60-75%
i. 75-80%
j. >80%

32. If spatial distribution is measured as the proportion of PELAGIC habitat occupied by yellow perch, what spatial distribution of yellow perch in the do you believe would lead to HIGH ecological consequences as defined above?

a. <10%
b. 10-15%
c. 15-20%
d. 20-25%
e. 25-35%
f. 35-50%
g. 50-60%
h. 60-75%
i. 75-80%
j.