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# Population Viability Analysis of inner Bay of Fundy Atlantic Salmon with and without Live Gene Banking

# Analyse de la viabilité des populations du saumon atlantique de l'arrière-baie de Fundy avec et sans banques de gènes vivants

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## ABSTRACT

The purpose of this Research Document is to provide background information on the population dynamics of inner Bay of Fundy (iBoF) Atlantic salmon in support of recovery planning for this designatable unit (DU). It covers issues in the Terms of Reference (TOR) for the iBoF Atlantic salmon Recovery Potential Assessment (RPA) related to abundance, trends, trajectories, recovery targets, and population viability. Abundance of iBoF salmon, which is thought to have been in the vicinity of 40,000 adults historically, has declined to less than a couple hundred adults presently in the wild. Bayesian analyses of abundance indices indicate a greater than 99% decline rate for these populations during the last 30 years. Electrofishing surveys for juvenile salmon in the early 2000's indicate that salmon are extirpated from many iBoF rivers. Two different population viability analyses (PVA), one based on trends in the Stewiacke River population and one based on the life history of the Big Salmon River population, indicate a high probability that this DU will become extinct in about one decade, in the absence of human intervention or a change in at-sea survival. At present, the primary intervention is a Live Gene Banking (LGB) program designed to minimize the loss of genetic diversity, such that the populations can be restored when conditions become favorable for their survival in the wild. Within this program, salmon are taken from the wild as they are migrating to sea, grown to maturity, and spawned in captivity. Unfed fry are then released back into the river to maximize exposure to the wild environment. This program thus bypasses the marine phase of the life cycle in which extremely high mortality rates are placing the population at risk. A life history based PVA that includes the LGB indicates a high probability that the population can be maintained through Live Gene Banking. In addition, this PVA was used to explore scenarios representative of 4 ways in which humans may impact on this DU: bycatch mortality in fisheries, incidental harm of juveniles via activity around rivers, downstream passage mortality at dams, and habitat restoration. In the absence of the LGB, the results indicate that at the present low at-sea survival rates, neither the probability of recovery (near zero) nor the probability of extinction (near one) is very sensitive to low levels of human-induced mortality. Similarly, at high at-sea survival rates, the probabilities of extinction or recovery are not very sensitive to low levels of human-induced mortality, although both the population recovery rates and the size of the recovered populations decrease with increasing mortality. Additionally, low levels of human-induced mortality have little effect on the probability of extinction (near zero) when the LGB is operating, even at very low levels of at-sea survival. A critical period exists when populations are beginning to recover, when both the probability of extinction and the probability of recovery are sensitive to low levels of mortality. The use of the conservation spawner requirement, a limit reference point used for salmon fisheries management, is proposed as a river-specific abundance recovery target. The number of rivers required for long-term persistence of the DU is not known, but the probability of persistence, ecological integrity of river ecosystems in which salmon were found, and human benefits are all increased if salmon are recovered in as many rivers as possible. Re-evaluation of the recovery targets and the effects of human-induced mortality, once populations are showing signs of recovery, is recommended.

## RÉSUMÉ

Le présent document de recherche vise à fournir des renseignements généraux sur la dynamique des populations de saumon atlantique de l'arrière-baie de Fundy à l'appui du plan de rétablissement pour cette unité désignable (UD). On y traite de questions liées au mandat de l'évaluation du potentiel de rétablissement (EPR) du saumon atlantique de ce secteur en ce qui concerne l'abondance, les tendances, les trajectoires, les objectifs de rétablissement et la viabilité des populations. Le nombre de saumons atlantiques de l'arrière-baie de Fundy, que l'on estimait à près de 40 000 adultes par le passé a diminué et on compte actuellement moins de quelques centaines d'adultes à l'état sauvage. Selon les analyses bayésiennes des indices d'abondance, le taux de déclin est de plus de 99 % pour ces populations au cours des trente dernières années. Les relevés par pêche électrique de saumons juvéniles qui ont été réalisés au début des années 2000 montrent que les saumons ont disparu de nombreux cours d'eau de l'arrière-baie de Fundy. Deux types d'analyses de la viabilité des populations (AVP), l'une fondée sur les tendances de la population de la rivière Stewiacke et l'autre sur le cycle biologique de la population de la rivière Big Salmon, indiquent qu'il est très probable que cette UD disparaîtra d'ici une dizaine d'années, en l'absence d'intervention humaine ou de changement du taux de survie en mer. À l'heure actuelle, la principale intervention consiste en un programme de banques de gènes vivants (BGV) destiné à réduire le plus possible la perte de diversité génétique, de telle manière que les populations puissent se rétablir lorsque les conditions seront propices à leur survie à l'état sauvage. Dans le cadre de ce programme, le saumon est prélevé à l'état sauvage au cours de son avalaison, élevé jusqu'à la maturité et amené à frayer en captivité. Les alevins vésiculés sont ensuite lâchés dans leur cours d'eau d'origine en vue de maximiser leur exposition au milieu naturel. Ce programme permet de sauter la phase marine du cycle biologique durant laquelle la population à risque est exposée à un taux de mortalité extrêmement élevé. Une AVP fondée sur le cycle biologique comprenant le recours aux BGV indique qu'il est fort probable que la population pourra être maintenue au moyen des BGV. De plus, cette AVP a été utilisée pour explorer des scénarios représentant quatre façons par lesquelles les êtres humains peuvent influer sur cette UD : mortalité accessoire dans les pêches, dommages incidents aux juvéniles dus à des activités se déroulant à proximité des cours d'eau, mortalité des saumons en dévalaison lors de leur passage dans les barrages et rétablissement de l'habitat. En l'absence de BGV, les résultats révèlent que pour les faibles taux actuels de survie en mer, ni la probabilité de rétablissement (proche de zéro), ni la probabilité de disparition (proche de un) ne sont très sensibles aux faibles niveaux de mortalité anthropique. De même, avec un taux de survie en mer élevé, les probabilités de disparition ou de rétablissement sont peu sensibles aux faibles niveaux de mortalité anthropique, quoique les taux de rétablissement et l'effectif des populations rétablies diminuent quand la mortalité augmente. De plus, de faibles taux de mortalité anthropique ont peu d'effet sur la probabilité de disparition (proche de zéro) quand il y a des apports des BGV, même quand la survie en mer est très faible. Lorsque les populations commencent à se rétablir, il y a une période critique durant laquelle la probabilité de disparition et la probabilité de rétablissement sont toutes deux sensibles à de faibles taux de mortalité. L'utilisation du nombre de reproducteurs nécessaires à la conservation, un point de référence limite employé pour la gestion de la pêche au saumon, est proposée comme objectif de rétablissement de l'abondance propre à chaque cours d'eau. On ne connaît pas le nombre de cours d'eau requis pour le maintien à long terme de l'UD, mais la probabilité de persistance, l'intégrité écologique des écosystèmes fluviaux dans lesquels le saumon a été observé et les avantages qu'en tirent les êtres humains augmentent tous s'il y a rétablissement du saumon dans le plus grand nombre possible de cours d'eau. On recommande qu'une réévaluation des objectifs de rétablissement et des effets de la mortalité anthropique soit effectuée une fois que les populations montreront des signes de rétablissement.

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## 1.0 INTRODUCTION

Abundance of inner Bay of Fundy (iBoF) Atlantic salmon, which includes populations occupying the region from the Mispec River, New Brunswick, to the Pereaux River, Nova Scotia, have declined precipitously during the last 2 decades. They are presently designated as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2006), and are listed on Schedule 1 of Canada's *Species at Risk Act* (SARA). Declines greater than 99% since the mid-1960's have been documented for some populations (Gibson and Amiro 2003; Gibson et al. 2003b), and electofishing surveys indicate that river-specific extirpations have occurred (Gibson et al. 2004).

The Department of Fisheries and Oceans (DFO) has established a protocol for ascertaining the feasibility of recovering species-at-risk (DFO 2007), termed a Recovery Potential Assessment (RPA). For species designated as threatened or endangered by COSEWIC, the RPA summarizes information about the status, trends, trajectories, threats, habitat requirements, and habitat availability to support the development of scenarios that could lead to recovery, to determine the social and economic costs of recovery, to provide information for public consultations, and to serve other jurisdictional functions regarding the decision about whether or not to list a species on Schedule 1 of SARA.

The conservation status of iBoF salmon has been reviewed by COSEWIC twice, initially in 1999 and again in 2006 (COSEWIC 2006). This document, prepared in support of a Recovery Potential Assessment for iBoF salmon in 2008, contains a summary and update of the information about the status, abundance, trends, trajectories, and recovery targets for populations within this designatable unit (DU). The section on abundance and trends is updated from previous documents. The section on recovery targets summarizes material in previous documents and includes a new analysis, which places the recovery targets in the context of past abundance and fishery reference points. The trajectories section includes a new analysis of the Stewiacke River abundance time series, as well as a life history-based Population Viability Analysis (PVA) for the Big Salmon River population. The goals of the trajectory analyses are to determine whether the populations are expected to become extinct or to recover in the absence of human intervention under current conditions. The PVA is then extended to include the effects of the Live Gene Bank (LGB) program on the extinction and recovery probabilities for iBoF salmon. By changing parameter input values, the PVA model was used to evaluate how extinction and recovery probabilities for iBoF salmon populations differ under a variety of freshwater production and marine survival scenarios, as well as under various kinds and levels of human-induced mortality.

Population viability analysis is a widely used technique in conservation biology to assess the extinction risk or recovery potential of a population in decline (Reed et al. 2002). Although uncertainty in model parameters and processes make predictions of future abundance uncertain (McCarthy et al. 2001), PVA is a powerful tool to explore current conditions, assess risks, and simulate how future management actions could affect a population in decline (Reed et al. 2002). The accuracy of stochastic population models in predicting future conditions depends on the appropriateness of model structure and input parameter values (Reed et al. 2002; Legault 2005). Life history modeling, which has a high degree of biological realism, was selected as a basis for the PVA (Trzcinski et al. 2004). A similar approach has been used to model Atlantic salmon populations in the Gulf of Maine (Legault 2005).

## 2.0 ABUNDANCE

Based on reported recreational catches and electrofishing data, Atlantic salmon are known to have occupied at least 32 rivers around the inner Bay of Fundy (Amiro 2003), although salmon may have occupied additional rivers in this area in the past. Historically, as many as 40,000 salmon likely returned to these rivers (Amiro 2003), an estimate supported by the extrapolation of recent estimates of abundance in 2 iBoF rivers (see below) to the size of the iBoF drainage area.

Population status of iBoF Atlantic salmon was typically assessed using data from 2 index rivers, the Big Salmon River, New Brunswick, and the Stewiacke River, Nova Scotia. Inference of trends obtained from the index rivers to other rivers around the inner Bay of Fundy was made based on recreational catch and effort data (prior to the closure of these fisheries), electrofishing data (from the index rivers, as well as several others), and adult fish counts on the Gaspereau River, N.S., and Upper Salmon River, N.B.

The collective status of all iBoF salmon populations was last updated in 2003 (Gibson et al. 2004). Since that time, status of the Big Salmon River population was updated to 2005 (juvenile densities and adult dive counts - Jones et al. 2006; smolt abundance estimates – Flanagan et al. 2006). Presently, DFO monitoring of abundance of iBoF salmon populations determines juvenile densities, adult returns, and smolt abundance estimates for the Big Salmon River population, adult returns for the Gaspereau River population, and smolt abundance estimates for the Stewiacke River. Parks Canada carries out adult counts, monitors smolt emigration, and estimates juvenile densities by electrofishing on the 2 rivers in Fundy Park: Point Wolfe River and Upper Salmon River. Using the monitoring data described above, the adult and juvenile abundance series are updated in this document, and are presented along with a summary of the abundance in other rivers from previous studies.

### 2.1 Gaspereau River

Adult returns to the Gaspereau River are monitored by counting the number of salmon ascending the fish ladder that bypasses the dam at the White Rock Generating Station. The number returning in 2007 was 2, down from 102 in 1997 (Table 2.1). Both were 1-sea-winter (1SW) salmon. Since 2001, all adults returning to the fish ladder have been collected for the LGB program; none have been released to spawn in the wild.

### 2.2 Big Salmon River

Each year, the number of adult salmon returning to the Big Salmon River is estimated by diver counts using a mark-recapture experiment (Gibson et al. 2004). In 2007, 28 salmon were observed during the survey (Table 2.2), which resulted in a population estimate of 47 salmon, down from 975 in 1989 (see also the Trends Section: Figure 3.1). Most (94%) of the salmon were 1SW fish. Juvenile densities within the Big Salmon River in 2007 were estimated to be 28.7, 24.7, and 2.5 fish/100m$^2$, for age-0 (fry), age-1, and age-2+ salmon, respectively. The age-1 density is the second highest in the 25 years for which data are available, likely as a result of LGB releases because adult abundance remains low (Table 2.3).

### 2.3 Upper Salmon River

Densities of juveniles increased in 2006 in the Upper Salmon River (Table 2.4) as a result of LGB releases. The mean density of parr (all age classes combined) in 2006 was 5.97 fish/100$m^2$, down from a high of 54.99 fish/100$m^2$ in 1985. Adult abundance is monitored by dive surveys, but total population size in the river cannot be calculated, because the proportion of the population observed (the observation efficiency) is unknown. In 2006, 1 grilse was observed during the survey, and in 2007, 1 large salmon was observed (Table 2.5). Based on the results of dive surveys in other rivers, observation efficiency is likely in the range of 25% to 60%, which implies that adult abundance remains low in this river. Between 1963 and 1994 (22 years), adult salmon were counted during autumn in the Upper Salmon River (Amiro 2003), and those results provide context for more recent observations. The highest recorded count was 1,200 fish in 1967, and 900 fish were counted in 1979 (Amiro 2003). Counts from 1991 to 1994 did not exceed 50 fish (Amiro 2003).

### 2.4 Point Wolfe River

In 2006, the mean density of parr in the Point Wolfe River was 0.78 fish/100$m^2$, which is the lowest value recorded on this river during the last 5 years (Table 2.6). The lower parr densities in the Point Wolfe relative to the Upper Salmon River are a result of adults (as opposed to juveniles) being released from the LGB into this river. Adult abundance is monitored by dive surveys, but the proportion of the fish observed is unknown. In 2006, 1 tagged (LGB) grilse was observed during the survey (Table 2.5). In 2007, 1 grilse which was not tagged was observed. As in the Upper Salmon River, the implication is that wild adult abundance remains low.

### 2.5. Other Rivers

Widespread electrofishing surveys have not been carried out within the inner Bay of Fundy since 2003. Gibson et al. (2004) summarized surveys in 2000, 2002, and 2003 (see also Gibson et al. 2003a). During 2002, the most extensive, recent electrofishing survey was undertaken to estimate the abundance of juvenile Atlantic salmon in all iBoF rivers. During the survey, a total of 246 sites were electrofished in 48 rivers (Figure 2.1). Of the 34 rivers without LGB support, fry were not found in 30 and parr were absent in 22 (Figure 2.2). Where salmon were present in rivers without LGB support, mean densities of fry (age-0) and parr (age-1 and age-2) were very low. On the New Brunswick side of the iBoF, mean densities of fry were less than 5.2 fish/100 $m^2$ and parr were less than 3.8 fish/100 $m^2$. On the Nova Scotia side of the iBoF in rivers without LGB support, fry were totally absent and mean densities of parr were less than 7.1 fish/100 $m^2$ (and were much lower in most rivers). During the electrofishing survey in 2003, 112 sites were electrofished in 16 rivers. Salmon were not captured in 5 of 10 rivers without LGB support and densities were low in the other 5 rivers. Overall, recent surveys suggest that densities are increasing in rivers with LGB support, but the box plots (Figure 2.2) indicate that salmon densities remain low in many parts of these rivers. In 6 of the rivers sampled, salmon were present at low densities in 2000 but were not found during 2002 or 2003, indicating that river-specific extirpations are ongoing.

Presently, not all salmon spawning in iBoF rivers are of iBoF origin. For example, genetic analyses have revealed that the salmon parr captured in the Harrington River in 2002 have a high incidence of European alleles and are quite dissimilar to iBoF salmon, although their exact origin is unknown. Subsequent electrofishing in 2006 did not find juvenile salmon in this river. If any of the juveniles detected in 2002 had returned to the river as adults and spawned successfully, their offspring would be expected to have been detected during 2006.

## 3.0 TRENDS

Index based, statistical models have been used to estimate the number of returning adults to the Stewiacke (Gibson and Amiro 2003) and Big Salmon (Gibson et al. 2003b) rivers for the years 1965-2001 and 1951-2002, respectively. These models were fit to the available data for each river (e.g., recreational catch and effort, fence counts, redd counts, dive counts, and juvenile densities obtained by electrofishing) and provide maximum likelihood estimates of annual abundance, exploitation, and sampling coefficients. Uncertainty in the estimates was evaluated using Bayesian methods, and the resulting time series were used to assess trends.

### 3.1 Stewiacke River

As of 2002, data for the Stewiacke River salmon population consisted of catch and effort data from the recreational fishery (27 years), estimates of juvenile densities obtained by electrofishing (23 years), an index of adult abundance obtained by electrofishing by boat (10 years), and counts of adults bypassing a fence (4 years). Using these data, the Stewiacke River population was estimated to be between 1,100 and 6,700 returning adults during the 1960's and early 1970's (Gibson and Amiro 2003), with high inter-annual variability (Figure 3.1). Estimates of the number of returning adults were less than 50 for the years 1997 to 2001, with a 90% probability that 4 or less salmon returned to the river in 2001. The analyses indicate a 90% probability that the population has declined by more than 99.6% between 1967 and 2000, and by more than 92% since the early 1990's (Figure 3.2). During the last 11 years, estimated population size was less than that calculated for the preceding year in all but 4 years. An electrofishing survey in 2003 did not find evidence of increased spawner abundance in subsequent years, although juvenile abundance has increased in the river as a result of the LGB program (Gibson et al. 2004).

### 3.2 Big Salmon River

The index-based models for the Big Salmon River salmon population were fit to recreation catch data, juvenile densities obtained by electrofishing, adult fence counts, stream-side and dive counts for adults, and redd count data (Gibson et al. 2003a). The analyses indicate a spawning run size in the range of 1,000 to 4,000 salmon during the 1960's and early 1970's, and a spawning run size of less than 100 fish from 1996 to 2002 (Figure 3.1). Estimates of the percent decline from the early 1990's ranged between 63% and 80%, and between 92% and 97% over the 30-year time period from 1967 to 2000 (Figure 3.2). Although adult abundance has remained low, juvenile abundance has recently increased in the Big Salmon River as a result of the LGB program.

## 4.0 POPULATION DYNAMICS PAST AND PRESENT

More information exists for the greatest number of life stages for the Big Salmon River population than for any other iBoF salmon population. Emphasis has been placed on modeling the dynamics of the Big Salmon River population for this reason. Trzcinski et al. (2004) analyzed the population dynamics of the Big Salmon River population from 1964 to present. They used maximum likelihood to fit a life history model to 9 data sets available for this population (Table 4.1). They compared 3 models of past dynamics: 1 in which the life history parameters (e.g., age- or stage-specific survivals, probabilities of smoltification at age, probability of maturing after 1 year at sea) were unchanged through time, 1 in which the life history parameters associated with the juvenile life stages in fresh water were allowed to change once during the time period, and 1 in which the life history parameters associated with

the adult life stages and marine environment were allowed to change once during the time period. The model that allowed changes in the marine environment provided the best fit to the available monitoring data and was the most biologically realistic. The analyses indicate: (1) a change in the annual mortality rate of immature salmon at sea from an average of 0.83 for the 1964-1989 time period to an average of 0.97 for the 1990-2003 time period, and (2) a change in the average annual mortality of post-spawning adult salmon from 0.49 (1964-1989) to 0.64 (1990-2003). Parameter estimates obtained from these analyses are reproduced here as Table 4.2. A limitation of the model is the averaging of the rates for each time period, which does not allow for ongoing (annual) changes in the parameter values. In particular, ongoing changes to at-sea mortality are likely. For the Gaspereau and Big Salmon rivers, return rates of salmon in 2003 were roughly 1 adult for every 300 wild smolt (Gibson et al. 2004), indicating much higher mortality in the marine life history stages than the 1990-2003 average calculated by Trzcinski et al. (2004).

## 5.0 TRAJECTORIES

As shown in Section 3, the Stewiacke River and Big Salmon River salmon populations have declined markedly during the last 2 to 3 decades. In this section, we evaluate the time to extinction if current trends continue. Two methods of PVA are used. For the Stewiacke River population, we use a Bayesian extension of a Dennis-type PVA, in which the population is projected forward using the rate of change in population size from year-to-year (Dennis et al. 1991). For the Big Salmon River population, we use a life history-based PVA, in which the population is projected forward using age- and stage-specific survivals and stage transition probabilities estimated from data from the Big Salmon River population. In both cases, random variability is incorporated into the model.

### 5.1 Stewiacke River

The population viability analysis presented here for the Stewiacke River population consists of 2 components. The first is the index-based assessment model for the Stewiacke population developed by Gibson and Amiro (2003), discussed in Section 3. The second component is a Dennis-type PVA model (Dennis et al. 1991), in which the population is projected forward using the equation:

(5.1) $$N_{t+1} = N_t e^{\log(\lambda_t)+\sigma\varepsilon_t}$$

where

(5.2) $$\lambda_t = N_{t+1} / N_t$$

and

(5.3) $$\varepsilon_t \sim N(0,1)$$

where $\lambda$ is the ratio of the population size in 1 year to the population size in the previous year, $\sigma$ is the standard deviation of $\lambda$, and $\varepsilon_t$ is a random deviate with a standard normal distribution. Gibson and Amiro (2003) used maximum likelihood methods to estimate the annual abundance of salmon in the Stewiacke River, and used Markov chain Monte Carlo methods to derive posterior probability densities for these parameters. The time series for the maximum likelihood estimates of $\log(\lambda_t)$ is shown in Figure 5.1. Prior to 1990, the population increased as often as it decreased. Since 1990, population has decreased in 8 of 12 years.

To carry out the population projections, we calculated the mean and standard deviation of $\log(\lambda_t)$ for the time period from 1990 to 2002, roughly 3 generations, for each of 1,000 iterations sampled from 1,000,000 iterations of the model (see Gibson and Amiro 2003 for details). The resulting posterior densities for these parameters (Figure 5.2) indicate that the mean of the mean rate of decline over this time period is 32% per year, with essentially zero probability that the population has increased in size during this time period.

Then, from each of the 1,000 iterations, we took the estimate of population size in 2002 and the estimates of the mean and standard deviation of $\log(\lambda_t)$, and projected the population forward for 100 years drawing random values of $\varepsilon_t$ from a standard normal distribution. The resulting population projections incorporate both the error associated with the estimates of population size and variability in the rate of change in population size from year to year. The 1,000 population projections are summarized in Figure 5.3. The results indicate about a 70% probability that this population would be extinct by 2012 in the absence of human intervention or some form of environmental change capable of reversing the trend. Although some trajectories increase slightly, all are extinct within 75 years.

### 5.2 Big Salmon River

The analysis of the Stewiacke River salmon abundance time series clearly shows that that population is at imminent risk of extirpation, a result consistent with the near-absence of juvenile salmon in non-LGB supported rivers observed during recent electrofishing surveys (Section 3). In this section, we use a life history based PVA to evaluate the probability that the Big Salmon River population will recover or extirpate given its present population size and population dynamics.

#### *Life History Model*

To describe the population dynamics of iBoF Atlantic salmon, we used the age- and stage-based life history model presented in Trzcinski et al. (2004):

Let the subscripts $t$, $a$, $c$, $ps$, and $s$ denote year, age, number of winters at sea (sea age), number of previous spawnings, and sex, respectively. The number of eggs at the start of the year ($Q_{t+1}$) is the product of the size specific fecundity ($f_{c,ps}$) and the number of returning spawners ($E_{t,a,c,ps,s}$) in the previous fall:

(5.4) $$Q_{t+1} = \sum_{t,c,ps} E_{t,a,c,ps,s} f_{c,ps} \quad .$$

The number of age-0 parr ($P_{t,0}$) in autumn of the first year is a function of egg deposition and the mortality rate of eggs. The mortality ($M^{Eggs}$) from time of egg deposition to the middle of the following summer multiplied by the number of eggs deposited in year $t$ gives the number of age-0 parr ($P_{t,a}$) in year $t+1$:

(5.5) $$P_{t,0} = Q_t(1 - M_t^{Eggs}) \, .$$

Density dependence was incorporated into the life cycle at the transition from age-0 to age-1, based on prior analysis by Gibson (2006). Furthermore, parr densities were scaled to total population size using an estimate of the number of habitat units ($h$) in the watershed. Therefore, the number of parr ($P_{t+1,a+1}$) of age *a* in year $t+1$ is given by 1 of 2 equations:

(5.6) $$P_{t+1,a+1} = \begin{Bmatrix} \dfrac{\alpha P_{t,a}}{1+(\alpha P_{t,a}/(\mathrm{R}_{\text{asy}}\,\mathrm{h}))}(1-j_{t,a}) & \textbf{if} \quad a=0 \\ P_{t,a}(1-M_t^{parr})(1-j_{t,a}) & \textbf{if} \quad a>1 \end{Bmatrix},$$

where $M^{Parr}$ is the mortality rate of parr and $j_{t,a}$ is the age-specific probability of smoltification. The age distribution data for Big Salmon River smolts suggests that nearly all parr undergo smoltification by age-3 (Jessop 1986; Flanagan et al. 2006), so $j_{t,3}$ = 1 in the model.

The number of immature salmon at sea in any year ($S_{t+1,a+1,c+1,s}$) is determined by 1 of 2 equations, depending on if the individual matures after 1 ($c=0$) or 2 ($c>0$) winters at sea:

(5.7) $$S_{t+1,a+1,c+1,s} = \begin{Bmatrix} P_{t,a}(1-M_t^{Parr})j_{t,a}v_s & \textbf{if} \quad c=0 \\ S_{t,a,c,s}(1-M_t^{Sea})(1-m_{t,c}) & \textbf{if} \quad c>0 \end{Bmatrix},$$

where $v_s$ is the proportion of males in the population, $M^{Sea}$ is the mortality rate of immature salmon at sea, and $m_{t,c}$ is the probability of maturing after 1 year.

The number of adults returning to the river to spawn ($N_{t+1,a+1,c,ps+1,s}$) is given by 1 of 2 equations, depending on whether or not the fish is a virgin ($ps=0$) or a repeat spawner ($ps>0$):

(5.8) $$N_{t+1,a+1,c,ps+1,s} = \begin{Bmatrix} S_{t,a,c,s}(1-M_t^{Sea})m_{t,c} & \textbf{if} \quad ps=0 \\ N_{t,a,c,ps,s}(1-M_t^{Adult})e^{-F_{t-1}} & \textbf{if} \quad ps>0 \end{Bmatrix},$$

where $e^{-F_{t-1}}$ represents the mortality associated with the recreational fishery.

Once in the river, fish that escape the recreational fishery contribute to the annual egg deposition, which is represented by:

(5.9) $$E_{t,a,c,ps,s} = N_{t,a,c,ps,s}(e^{-F_{t,c,ps}}).$$

***Population Viability under Current Conditions***

Although we used the population model of Trzcinski et al. (2004) to describe the present dynamics of the population, we modified the manner in which variability was incorporated into future mortality rates, sex ratio, and maturity schedules for greater biological realism (Shelton et al. 2007). Initial mean values for each parameter were taken from the life history model output for iBoF salmon populations (Table 4.2). However, instead of incorporating random variability on the logistic scale for each parameter, we assumed a lognormal distribution for the deviates around the mortality parameters and logistic distribution for the maturity and sex ratio parameters. Lognormal distributions are often used to model the deviates around survival functions as survival is multiplicative in nature (Hilborn and Walters 1992). Given that sex ratio and maturity are proportions, the logistic transformation better describes the binomial nature of their error distributions.

Deviates would be expected to be temporally autocorrelated (Hilborn 2001), given that the effect of environmental variability on population vital rates tends not to be completely random (Lande et al. 2003). As the strength of this autocorrelation increases, good years are increasingly likely to be followed by good years (and bad followed by bad). Experimentally derived estimates for

the strength of temporal autocorrelation were not available, so plausible values were assumed for the freshwater and marine environments (Table 5.1) and were incorporated into the following equations.

Lognormal transformation:

Let $\overline{M}$ equal the instantaneous rate of mortality affecting a life stage of salmon (as estimated using the BSR life history model) and $\sigma_w$ equal the standard deviation of the residuals of the mortality rate. Intantaneous mortality in year $t$ becomes:

(5.10) $$M_t = \overline{M} \exp(w_t - \sigma_w^2 / 2)$$

where

(5.11) $$w_t = w_{t-1} d + w_t \sigma_w$$

and

(5.12) $$w_t \sim N(0,1)$$

where $d$ is a constant describing the degree of autocorrelation and $w$ is a set of normally distributed random numbers (Hilborn 2001).

Now $M_t$ could be used to describe survival between 2 life stages, following the general format of:

(5.13) $$N_{t+1} = N_t \exp(-M_t)$$

For the population projection model used in the PVA (above), the random variability in the parameters $M_t^{Egg}$, $M_t^{Parr}$, $M_t^{Sea}$, and $M_t^{Adult}$ was modeled in this fashion.

Logistic transformation:

Let $p$ equal a parameter value in the form of a proportion. The logit mean of the parameter ($S$) becomes:

(5.14) $$S = \ln(p/(1-p))$$

Autocorrelated random deviates for $t$ years are calculated by:

(5.15) $$w_t = w_{t-1} d + w_t \sigma_w$$

and

(5.16) $$w_t \sim N(0,1)$$

where $d$ is a constant describing the degree of autocorrelation, $\sigma_w$ is the standard deviation of the residuals of the parameter value and $w$ is a set of normally distributed random numbers (Hilborn 2001).

The annual probability becomes:

(5.17) $$p_t = \exp(S + w_t)/(1 + \exp(S + w_t))$$

where $p_t$ would describe the probability of being in 1 state or the other (e.g., immature or mature) at any given time.

The goal of the PVA was to determine how the population's abundance trajectory would be expected to change and to assess the probability of meeting recovery targets, as well as to quantify extinction risk over a biologically reasonable timeframe. Given the adult population estimates for the Big Salmon River as well as the ratio of 1-sea-winter to multi-sea-winter (MSW) adults returning (Table 2.2), we set the starting population size to be 50 individuals, 37 1SW and 13 MSW salmon. In the freshwater component of the population projection model,

we followed Trzcinski et al. (2004) in assuming that density dependence affects the survival of age-0 to age-1 parr, and that all parr undergo smoltification by age-3. In the marine component of the model, we modeled males and females separately in order to account for the sex ratio observed in the Big Salmon River population. All wild adults were assumed to spend no more than 2 years at sea before returning to spawn, and were able to spawn up to 5 times. Recent evidence suggests that the marine mortality rates presently experienced by iBoF salmon are higher than those estimated in 2004 (Gibson et al. 2004), so we used a value of 99% to represent current conditions. Fishing mortality was assumed to be zero for this simulation.

Abundance trajectories and their associated uncertainty were assessed by running 500 simulated trajectories of the population, summarized by the median, $10^{th}$, and $90^{th}$ percentiles of the resulting distribution for each year. We defined an extinction threshold for the population as being the occurrence of 2 consecutive years where egg deposition was less than that expected from 1 small female salmon (3232 eggs). Strictly speaking, true extinction occurs when no individuals of any life stage are present; however, the extinction threshold represents a functional definition where population size is so small that true extinction is imminent. The probability of extinction for the PVA becomes the percentage of model runs at or below the extinction threshold in each year. Similarly, the probability of meeting the recovery target becomes the percentage of model runs that meet or exceed the target egg deposition value. Recovery targets for Atlantic salmon in Atlantic Canada have been derived from conservation egg requirements calculated for major watersheds. In the inner Bay of Fundy, these are based on the amount of available habitat in a watershed multiplied by a target egg deposition rate of 2.4 eggs/$m^2$ (Marshall et al. 1999). For the Big Salmon River, this value is 2.18 million eggs.

***Results***

We calculated the expected abundance trajectories, probability of meeting the recovery target, and extinction probabilities under present freshwater and marine conditions. Starting with 37 small and 13 large adults, the population was projected forwards 50 years. Figure 5.4 summarizes a single run of the PVA projection model, showing the abundance trajectory for each life stage. For this run, each life stage trends to zero within 10 years.

A similar pattern was found when 400 iterations of the projection model were run. Egg deposition was projected to decline sharply to zero under current conditions (Figure 5.5) and nearly all of the 400 simulated trajectories were extinct within 12 years. The population is not predicted to be viable, and, as expected, the probability of meeting the recovery target remains zero throughout the 50 year timeframe (Figure 5.5).

## 6.0 RECOVERY TARGETS

### 6.1 Background

With little change in intent, recovery targets for iBoF salmon have evolved from: generic statements about the goals of the recovery strategy (National Recovery Team 2002), to quantitative recovery targets in an unspecified set of rivers in the present draft of the recovery strategy (DFO 2006a). Here, we review information leading to the development of the goals for recovery, and provide additional information about the magnitude of the recovery targets relative to abundance of iBoF salmon before their decline.

The National Recovery Strategy for inner Bay of Fundy Atlantic Salmon (National Recovery Team 2002) lists the goals of the strategy as:

> "*1.1 Short-Term*
> To re-establish wild self-sustaining populations as required and to preserve the remaining genetic diversity of the lineage of iBoF salmon.
>
> *1.2 Long-Term*
> To re-establish wild iBoF salmon populations in all salmon producing rivers and streams within the iBoF. *"*

This long-term goal is consistent with the ideas that: (1) the probability of attaining long-term population persistence, (2) the ecological function of the watersheds in which salmon formerly resided, and (3) the potential for human benefits would all be increased if populations were recovered in as many rivers as possible. At the same time, it was recognized that the number and size of populations required for restoring stability to the iBoF salmon DU is not known. The strategy recommended that a prioritized approach to recovery, beginning with the protection of what remains of the residual populations, followed by restoration of self-sustaining populations in the 2 principal population groups (in the Chignecto and Minas Basins) and the Gaspereau River population, followed by "the restoration of iBoF salmon to the 24 rivers in which they were known to be present in 1989 (i.e., immediately before the onset of the decline that has occurred)." This later goal was intended as an intermediate milestone to restoring salmon to all iBoF rivers which produced salmon.

Although SARA does not specifically state that quantitative recovery targets are required in a recovery strategy, quantitative recovery targets are needed in order to assess progress towards recovery and to ensure that management under the SARA is consistent with management under the *Fisheries Act*, where quantitative reference points are used (DFO 2005). The recovery goal in the most current draft of the recovery strategy (DFO 2006a) thus reads:

> "*to conserve the genetic diversity of the few remaining anadromous iBoF Atlantic salmon populations to the extent possible and restore self-sustaining populations of iBoF Atlantic salmon populations to conservation levels throughout the iBoF, where practically and technically feasible."*

This version of the recovery strategy includes 2 parts to the goal: (1) attainment of the conservation spawner requirement within a river (an abundance goal), and (2) a set of rivers in which salmon are to be recovered (a distribution goal), although the latter is not specified in the November 2006 draft.

### 6.2 The Conservation Spawner Requirement as a River-Specific Recovery Target

The rationale for use of the conservation spawner requirements (CSR) as recovery targets (DFO 2006b) is based primarily on their use in the management of salmon populations in eastern Canada (CAFSAC 1991a, 1991b), but also on their magnitude (roughly 25% the past abundance of iBoF salmon, see below). Within the Maritime Provinces, the conservation spawner requirements are river-specific estimates of the number of salmon required to produce egg depositions of 2.4 eggs/$m^2$ of habitat, with the exception of the LaHave River where an interim lower value is used because of the uncertainties surrounding the effect of acidification. The status of salmon populations in the Maritimes is presently assessed by comparing population sizes to these conservation spawner requirements, and management actions to

conserve or restore salmon populations are initiated based on status relative to these requirements.

Chaput (2006) reviewed the derivation of the conservation spawner requirement beginning with the initial proposal of Elson (1957) that 2 eggs/yd$^2$ (2.4 eggs/m$^2$) would maximize smolt production, a value that has been reviewed many times. Following the 1990 Supreme Court of Canada decision in the case of Regina vs. Sparrow, which recognized that native food fisheries have first right of access to natural renewable harvestable resources once conservation was assured, a definition of the conservation needs for salmon was required. In response to this need, a subcommittee of the Canadian Atlantic Fisheries Scientific Advisory Committee (CAFSAC) adopted the egg deposition rate of 2.4 eggs/m$^2$ of fluvial rearing habitat as the level below which CAFSAC would strongly recommend that no fishing should occur. CAFSAC considered that this level provided a modest margin of safety, and that the further a spawning escapement was below the CSR, and the longer it was below the CSR (even at levels only slightly below), the greater the possibility of incurring risks that could lead to irreversible damage to the stock (CAFSAC 1991a). Risks to the populations included:

> "*accentuation of annual fluctuations in run size and reduction in the long-term capability of the stock to sustain native food fisheries, recreational fisheries, or commercial fisheries; increased susceptibility to extinction from genetic, demographic, or environmental catastrophes and consequent decreases in productivity; permanent changes in demographic characteristics of the spawning population; [and] replacement in the ecosystem by other competing fish species of potentially less social and economic value*." (CAFSAC 1991a).

DFO (2005) summarizes the outcome of a national workshop held to consider what constitutes recovery in the context of species-at-risk, where participants attempted to derive recovery targets consistent with the framework for application of the precautionary approach in science advice on fisheries harvests. This framework has 3 zones:

> "*Critical: Zone where stock biomass is evaluated as being at or below a level where there is a high risk of serious or irreversible harm to stock productivity. When stock biomass is within this zone, exploitation rates should be as low as possible, with no directed fisheries and practical bycatch reduction measures in place. Rebuilding of the stock should be the sole consideration in allocating surplus production.*
>
> *Healthy: Zone where stock biomass is evaluated as being within the historical range of the stock when science advisors did not recommend that priority be given to rebuilding the stock. When stock biomass is in this zone, exploitation should be at rates which are sustainable in the long-term, but social and economic considerations are the main factor in deciding what proportion of surplus production from the stock should be devoted to harvests.*
>
> *Cautious: Zone between the Critical and Healthy Zones, which reflects uncertainty about the estimation of annual stock status and the biomasses at which stock productivity begins to decline and becomes at risk of serious or irreversible harm. Exploitation rate should decline progressively from sustainable in the long-term at the Healthy-Cautious Boundary to as near zero as possible at the Cautious-Critical Boundary, as the priority given to stock rebuilding grows and the priority given to social and economic uses of surplus production declines.*" (DFO 2005).

This framework was used as a starting point for determining the state of a species or population when it is recovered, and the use of both the critical-cautious boundary and the cautious-healthy boundary as recovery targets were reviewed at the workshop. While both positions had strengths and weaknesses, it was concluded that "*any reasonable description of "recovery" would be at least a stock healthier than either the Critical-Cautious boundary or the risk criteria of COSEWIC*" (DFO 2005).

Exactly where the CSR falls within this framework is not known. As discussed by Chaput (2006), although initial work on which the use of 2.4 eggs/$m^2$ as a reference point was couched in language consistent with a target value (which would be nearer the cautious-healthy boundary), its adoption and application has been more consistent with a limit reference point (which would be nearer the critical-cautious boundary), as evidenced by the above quote from CAFSAC (1991a). Some of the confusion associated with this value stems from the development of the conservation spawner requirement prior to the development of either the target-limit terminology for fisheries reference points or the precautionary framework for fisheries management. Below, we review the conservation spawner requirement for iBoF salmon populations in the context of past abundance, as well as past and present dynamics to aid in the determination of whether it is appropriate as a recovery target, and whether it is nearer the critical-cautious boundary or the cautious-healthy boundary of the precautionary fisheries management framework.

DFO (2006) provides the CSR for 25 rivers for which the habitat amount has been quantified (Table 6.1), which totals 9,919 fish. In comparison, the historical total abundance of salmon in the iBoF designatable unit was estimated to be more than 40,000 fish (Amiro 2003). Given that any excluded rivers are relatively small, the CSR for these rivers are unlikely to exceed more than a few percent of that of the full iBoF DU. As such, the use of the CSR as a recovery target would place the target at about one-quarter the estimated past abundance of salmon in this area. Additionally, where river-specific historical abundance estimates are available, the requirement does not appear unduly large relative to past abundance. For example, the conservation spawner requirement for Stewiacke River is 772 small salmon and 289 large salmon. These values were exceeded most years from 1964 to 1985 (when both commercial and recreational fisheries were ongoing), at times by a factor greater than 2 (Gibson and Amiro 2003). Similarly, pre-decline abundance on Big Salmon River, where the CSR is 700 fish (280 small and 420 large salmon), at times exceeded 5,000 salmon (Gibson et al. 2003b). In summary, the CSR as a recovery target is not high relative to past abundance.

A spawning biomass of 20% $B_{eq}$ (the unfished equilibrium biomass) has been proposed as a minimum threshold population size (Beddington and Cooke 1983; Goodyear 1993), and Myers et al. (1994) suggested that the stock size corresponding to 50% the maximum average recruitment (the *K* parameter in the Beverton-Holt SR model) could be interpreted as a minimum biomass level at which recruitment to a fish stock is seriously reduced. Both of these proposals for limit reference points are thus candidates for the critical-cautious boundary in the precautionary fisheries management framework. The life history parameter estimates presented in Table 4.2 are sufficient for an equilibrium analysis that can be used to determine the relative magnitude of the CSR with respect to these reference points. The equilibrium plot, overlaid with the conservation requirement in Figure 6.1, illustrates that the conservation requirement is well below the equilibrium population size estimated for the earlier time period. The freshwater production curve (fit to 9 data sets) is shown together with the egg depositions and cohort smolt production for the years 1966 to 1971 and 2001, and illustrates that the predicted carrying capacity is well above the maximum observed smolt abundance (Figure 6.1). The equilibrium egg deposition, calculated using the marine survival estimates from the older data (pre-1971), is 23.7 million eggs. Using the present survival rate estimates (2001), the equilibrium is zero.

In the case of the Big Salmon River population, the conservation requirement is 2.18 million eggs (Table 6.1) or just under 10% the equilibrium egg deposition based on the life history parameters prior to the decline and about 1/5 of K (11.2 million eggs). From this comparison, the CSR would be nearer to the critical-cautious boundary than the cautious-healthy boundary of the precautionary fisheries management framework and is not overly high as a recovery target.

Given that all the observed spawner abundances are low relative to the predicted equilibrium, some uncertainty exists in the estimated carrying capacity for Big Salmon River. To aid in addressing this concern, we fit a Beverton-Holt stock recruitment model to observed egg deposition and smolt abundance data. In this case, the predicted carrying capacity was slightly greater than 25,000 smolts, and the predicted equilibrium was about 7 times the conservation requirement. This analysis does not change the conclusions of the preceding paragraphs that the CSR is not an unrealistically high recovery target.

If populations around the iBoF begin to recover, it is likely that recovery targets will need to be re-evaluated, as research about salmon population dynamics continues and further knowledge about the balance between freshwater production and marine survival in recovering populations is obtained. However, given the information above, it does not appear likely that the river-specific reference values will be lower than their CSR.

### 6.3 Number of Populations Required for Recovery

The issues associated with establishing a river-specific abundance recovery target in the absence of knowledge of the dynamics of recovered populations also applies to establishing the number of rivers in the recovery target. There is additional uncertainty associated with the importance of migration among rivers for ensuring numerical stability and genetic integrity within the DU. However, there are several aspects of the DU, as well as salmon life history and variability, which indicate that recovering as many populations as feasible will increase the probability that the DU will be self sustaining in the long-term. These characteristics also aid in the selection of distribution targets for the DU.

First, there is population and genetic structuring with the iBoF salmon DU. Based on analyses of mitochondrial DNA (Verspoor et al. 2002), iBoF Atlantic salmon can be further partitioned into 2 groups of populations that are both genetically and geographically separated: the Minas Basin subunit (populations in rivers flowing into the Minas Basin) and the Chignecto Bay subunit (rivers flowing into Chignecto Bay and directly into the Bay of Fundy from New Brunswick. Additionally, the Gaspereau River population is unique in that it is genetically similar to populations in the Minas Basin subunit, but displays marine migratory patterns and life history traits similar to outer Bay of Fundy salmon (Amiro and Jefferson 1996; DFO 2001). Although the importance of these differences is not known, it is suggestive that local adaptation to different iBoF environments has occurred and restoration of these groups would, therefore, increase the probability of long-term persistence of the entire iBoF group.

Second, there is local habitat variation within both the Minas Basin and Chignecto Bay regions that would be expected to lead to further local adaptation, thereby requiring the maintenance of additional diversity. Maintenance and restoration of this variation is again expected to increase the probability of long-term persistence by enhancing the potential for successfully adapting to environmental changes. Although variation exists both on other spatial scales (particularly smaller) and within other habitat attributes, river gradient is known to vary around the inner Bay of Fundy. For example, rivers on the north side of the Minas Basin tend to be of higher gradient than rivers on its south shore, and rivers flowing into the outer part of Chignecto Bay or directly

into the Bay of Fundy tend to be of higher gradient than rivers in the inner part of Chignecto Bay (Amiro et al. 2003; Trzcinski et al. 2004).

Third, increasing the number of populations being used to maintain local variation decreases the risk of extirpation as a result of catastrophic events.

Fourth, protection and recovery of populations in larger rivers (e.g., the Petitcodiac and Big Salmon in the Chignecto Bay subunit, and the Stewiacke and Salmon River in the Minas Basin subunit) would likely aid in the recovery of populations in other rivers. Fraser et al. (2007) showed that larger rivers (Stewiacke, Petitcodiac, and Big Salmon in their study) are better source populations for emigration and colonization than are smaller rivers. The Upper Salmon River was naturally re-colonized after removal of dams in the late 1960's (Dadswell 1968) and the Big Salmon River population was the main source for this re-colonization (Fraser et al. 2007).

Fifth, at present the importance of straying and mixing among populations for maintaining iBoF salmon populations is not known, yet metapopulation structure is known to be an important consideration in the conservation of salmonids (Cooper and Mangel 1999). It can increase regional persistence, particularly when dispersal "rescues" a local population from extirpation (Hanski 1998), and even low straying rates have been shown to prolong regional persistence (Hill et al. 2002, Legault 2005). It follows that the probability of long-term persistence of iBoF salmon would be expected to increase as the number of rivers in which salmon are recovered is increased.

Based on the information above, restoration of salmon populations in the rivers in which they have been known to occupy either prior to their most recent decline, or were known to have occupied historically, have been proposed as candidates for the population distribution component of the recovery target. Although at present, neither position can be fully justified scientifically. A sufficiently large subset of these rivers could be selected if the practical aspects of recovering salmon in a specific river are limiting, although as mentioned earlier in this section, population viability, ecological function, and human benefits are increased if populations are recovered in as many rivers as is feasible.

Finally, as was the case with the use of the CSR as a river-specific abundance target, it is likely that the distribution target will need to be revisited once knowledge about the dynamics of the recovered populations is obtained. Thus, the possibility exists that the number of rivers may be reduced if fewer rivers meeting their CSR are demonstrated to be sufficient for persistence. Alternatively, it is also possible that more rivers or increased access to rivers may be required.

## 7.0 POPULATION VIABILITY ANALYSES WITH AND WITHOUT LIVE GENE BANKING

A Live Gene Bank program was initiated for the DU in 1998, with the goal of preserving the remnant populations and remaining genetic diversity of inner Bay of Fundy Atlantic salmon (Gibson et al. 2004; O'Reilly and Doyle 2007). To determine the potential affects of the LGB program on population viability and recovery, we modified the PVA projection model to incorporate an annual contribution of LGB fish into the wild population. The current LGB program was designed to address the issue of extremely high marine mortality rates affecting Atlantic salmon by collecting juvenile salmon from the wild, raising them to maturity in captivity, and releasing the offspring of these fish back into the donor river (Gibson et al. 2004; O'Reilly and Doyle 2007). As such, it incorporates many redundancies and back-ups in case of catastrophic events, and this complexity could not be fully accounted for in the PVA projection

model. We used a simplified version of the current LGB program whereby smolts are collected on their seaward migration, raised to maturity in a hatchery, spawned, and the resulting progeny are stocked back into their natal river as unfed fry. This ensures that juveniles of wild and of LGB origin would be exposed to analogous selective pressures in the river environment, which should result in equivalent mortality rates and stage-specific transition probabilities among individuals.

### 7.1 PVA Adaptations to Incorporate the LGB

To incorporate the contribution of the LGB program to the wild population into the PVA projection model, several parameters were added (Table 7.1). We modeled the annual smolt collection for the LGB program to consist of the same age proportion of wild- and LGB-origin smolts as exist in the river, given that the rotary screw trap used for collection is indiscriminate to origin. Presently, a total collection of 150 smolts annually is possible given the space available at the biodiversity facility. The maturity schedule for LGB adults was assumed to differ from wild fish, with a larger proportion of the population maturing after 1SW (Table 7.1). LGB adults were allowed to spawn once in the hatchery and then were assumed to die. Fishing mortality was assumed to be zero for all simulations of present conditions.

The population projection model from Section 5 was modified as follows: Let the subscripts $t$ index the year, $a$ age, $s$ sex ("m" or "f"), $c$ the number of winters a smolt remains at sea prior to spawning for the first time, and $ps$ the number of times a fish has previously spawned. The number of wild fish entering the river to spawn in a given year is denoted as $N_{t,a,c,ps,s}$ and the number of LGB fish available to spawn is $N^{LGB}_{t,a,c,ps,s}$. The model increments annually on January 1 and for simplicity, we assume that the eggs physically laid in autumn are actually laid on the first day of the next year.

Egg production:

For wild fish, the number of eggs produced in the next year, $Q_{t+1}$, is a function of the number of returning females, $N_{t,a,c,ps,f}$, and female fecundity at each spawning event, $f_{c,ps}$:

(7.1) $$Q_{t+1} = \left( \sum_{a,c,ps} N_{t,a,c,ps,f} f_{c,ps} \right).$$

For LGB fish, the number of eggs produced in the next year by broodstock, $Q^{LGB}_{t+1}$, is a function of the number of mature females, $N^{LGB}_{t,a,c,0,f}$, and female fecundity at their first spawning event, $f_{c,0}$:

(7.1a) $$Q^{LGB}_{t+1} = \left( \sum_{a,c} N^{LGB}_{t,a,c,0,f} f_{c,0} \right).$$

Production of age-0 parr:

Let $P_{t,0}$ be the number of parr in year $t$ of age-0. The total population of age-0 parr is the sum of the wild production in the river and the releases from the LGB program. Given that eggs become age-0 fry in the same year that they were laid, the relationship between the number of parr at age-0 in year $t$ and egg production in year $t$ is:

(7.2) $$P_{t,0} = Q_t(1-M_t^{Egg}) + Q_t^{LGB}(1-M_{LGB}^{Egg})T_{LGB}^{fry},$$

where wild egg mortality varies in each year due to autocorrelated environmental stochasticity (see Section 5), but egg mortality of LGB progeny in the hatchery ($M_{LGB}^{Egg}$) is assumed to be constant. It has been documented that the survival rates of wild juveniles are higher than those of hatchery-reared juveniles released into the wild. Therefore, we correct for differential survival with the parameter $T_{LGB}^{fry}$. This is equivalent to the assumption that mortality rates are high when individuals are first released into the wild. However, in subsequent years, we assume that the mortality experienced by juveniles of LGB origin is equivalent to that experienced by those of wild origin.

Production of age-1+ parr:

Natural mortality during the first year is best described as a density-dependent function in the Big Salmon River (Gibson 2006). Here we use a Beverton-Holt model to describe the nature of the density-dependent relationship, and to determine the number of age-1 parr in year $t+1$. The number of age-2 and age-3 parr is calculated as the number of parr the previous year less the density-independent parr mortality and the number that undergo smoltification. Note that wild fish are indistinguishable from LGB fish. We define $j_{t,a}$ as a vector containing the annual age specific probabilities that a parr develops into a smolt and emigrates to sea the following year, accounting for variation among years (see Section 5):

(7.3) $$P_{t+1,a+1} = \begin{Bmatrix} \dfrac{\alpha P_{t,a}}{1+(\alpha P_{t,a}/(\mathrm{R_{asy}h}))}(1-j_{t,a}) & \textbf{if} \quad a=0 \\ P_{t,a}(1-M_t^{parr})(1-j_{t,a}) & \textbf{if} \quad a>1 \end{Bmatrix}$$

Production of immature salmon:

The number of immature salmon at sea in year $t+1$, of sex $s$, age $a+1$, in sea-age class $c$ is denoted as $S_{t+1,a+1,c,s}$. We define the vector $m_{t,c}$ as the probability that an immature salmon in sea-age class $c$ matures in a given year, allowing for variation among years (see Section 5). The number of smolt exiting the river each year and the number of immature salmon at sea is given by 2 equations:

(7.4) $$S_{t+1,a+1,c+1,s} = \begin{Bmatrix} P_{t,a}(1\text{-}M_t^{Parr})(j_{t,a}) - LGB_{t,a,s}^{collection} & \text{if} \quad c=0 \\ S_{t,a,c,s}(1\text{-}M_t^{Sea})(1-m_{t,c})v_s & \text{if} \quad c>0 \end{Bmatrix},$$

where the LGB collection is taken randomly from the total smolt population as it exits the river, and has the same proportion of individuals at age $a$ and of each origin (wild or LGB) as the remaining smolts. When the population is large, the number of smolts collected for the LGB program is the same every year, based on hatchery capacity. When the population of smolt in any year is smaller than 10 times the collection value, 10% of the emigrating smolts from that year are collected. At small population sizes, the proportion of the population removed reflects the efficiency of the rotary screw trap used to collect smolts. Once the LGB collection reaches the hatchery, the number of immature LGB salmon the following year is given by:

(7.4a) $$S_{t+1,a+1,c+1,s}^{LGB} = LGB_{t,a,s}^{collection}(1-M_{LGB}^{Smolt})(1-m_{t,c}^{LGB}) \qquad \text{if} \quad c>0,$$

where $M_{LGB}^{Smolt}$ is the mortality rate of smolts as they are transported to the hatchery. The LGB smolts are assumed to have the same maturity schedule as the wild population.

Production of adults:

Similarly, the number of fish returning to the river to spawn ($N_{t+1,a+1,c,ps,s}$) is given by 2 equations, depending on whether or not the fish is a first time spawner ($ps = 0$) or a repeat spawner ($ps > 0$). As in previous equations, variability in mortality rates and the maturation schedule are incorporated into the yearly parameter values (see Section 5):

(7.5) $$N_{t+1,a+1,c,ps,s} = \begin{cases} S_{t,a,c,s}(1\text{-}M_t^{Sea})(m_{t,c}) & \textbf{if} \quad ps = 0 \\ N_{t,a,c,ps,s}(1\text{-}M_t^{Adult}) & \textbf{if} \quad ps > 0 \end{cases}.$$

Because LGB fish are permitted to spawn only once in the hatchery, the number of mature spawners ($N^{LGB}_{t+1,a+1,c,ps,s}$) is given by 1 equation:

(7.5a) $$N^{LGB}_{t+1,a+1,c,ps,s} = S^{LGB}_{t,a,c,s}(1 - M^{Adult}_{LGB})(m^{LGB}_{t,c}) \qquad \text{when} \;\; ps = 0.$$

where $M^{Adult}_{LGB}$ is the mortality rate of adults within the hatchery. Random variability was incoprorated into the model using the methods described in Section 5. In these model runs, an extinction threshold was set at 10 females.

### 7.2 Scenario Analyses With and Without the LGB

To investigate how salmon populations in the inner Bay of Fundy might be expected to respond to human activities in the freshwater or marine environments, we performed 4 scenario analyses using the PVA projection model described above. These scenarios were meant to explore the scope for management to facilitate recovery and to model the potential outcomes of future management strategies. In all scenarios, the mortality rate of immature salmon at sea varied from current estimates (99%) down to levels expected to lead to recovery (92%). Each scenario was modeled with and without the contribution from the Live Gene Bank to determine the LGB's effect on both the probability of recovery and the probability of extinction. There is a general consensus that marine mortality is presently the main cause of the decline in iBoF salmon populations (COSEWIC 2006; Gibson et al. 2004; Jones et al. 2006); however, habitat loss, habitat degradation, and reduced access to rivers have the potential to limit recovery as well.

The scenarios are intended to be representative of many activities that may impact on salmon population dynamics, including:

(1) Increased freshwater productivity, resulting in greater smolt production within the river. This scenario is intended to represent freshwater habitat restoration activities.
(2) Increased mortality from fisheries in the marine environment. This scenario is intended to be representative of the effects of bycatch mortality in marine fisheries and acts on both mature and immature salmon at sea.
(3) Increased mortality for smolts and adults while migrating downstream at hydroelectric facilities. This source of mortality acts on smolts prior to reaching the ocean as well as on post-spawning adults returning to the sea.
(4) Increased freshwater mortality for juvenile parr (ages 0 to 2). This scenario is intended to be representative of the mortality of parr as a result of human activities such as wading, culvert construction or repair, and bycatch in recreational fisheries.

The same variation in at-sea mortality (99%, 97%, 94%, and 92%, respectively) was incorporated for each.

***Scenario 1: Increased Freshwater Productivity***

In this scenario, freshwater productivity was modeled both at current levels and at incremental increases of 5%, 10%, and 25% for other simulations. This change affected the asymptotic recruitment level ($R_0$) and maximum annual survival rate of age-1 parr ($1-M^{Parr}$), such that $R_0$ equalled 87.1, 91.5, 95.8, and 108.9, respectively, and $M^{Parr}$ equalled 0.949, 0.900, 0.854, and 0.726, respectively. The main goal of habitat restoration projects is to increase freshwater productivity, which presumably would result in larger juvenile population sizes in the available habitat and greater subsequent smolt production.

***Scenario 2: Increased Fishing Mortality***

Even though all commercial fisheries directed at adult salmon at sea were closed in 1985 (Amiro et al. 2003), some level of bycatch mortality by other commercial fisheries might be expected. Increases in bycatch fishing mortality ($M^{Fish}$) was modeled assuming fishing mortality rates of 0%, 2.5%, 5% or 10% respectively on the total adult abundance. This was incorporated into the PVA projection model by multiplying the right-hand side of both parts of Equation 7.5 by:

(7.6) $$(1-M^{Fish}).$$

***Scenario 3: Downstream Passage Mortality at Hydroelectric Dams (Smolts and Adults)***

Downstream passage at hydroelectric generating stations can result in smolt and adult mortality as individuals migrate from the freshwater environment to the sea. This was incorporated into the PVA by multiplying the right-hand side of Equation 7.4 (when $c=0$) and Equation 7.5 (when $ps>0$) by:

(7.7) $$(1-M^{Turb}),$$

assuming values of 0%, 10%, 25% and 50%. For simplicity, values were assumed to be the same for both smolts and adults. This scenario was intended to represent the impact of further hydroelectric development on rivers in the iBoF.

***Scenario 4: Increased Incidental Juvenile Mortality***

Activities that result in physical disturbances in rivers, as well as bycatch in riverine fisheries, could result in incidental mortality of juvenile salmon. Such mortality was assumed to affect all juvenile life stages equally, and reduced abundance in each age class by 0%, 2.5%, 5%, and 10%, respectively. This was incorporated into the PVA by multiplying the right-hand side of Equations 7.3 and 7.4 (when $c=0$) by:

(7.8) $$(1-M^{Incidental}).$$

**7.3 Results**

A comparison of a single simulation from the PVA with and without the LGB under current survival rates is shown in Figure 7.1. In contrast with the simulation without the LGB, with the contribution from the LGB program to the population, each life stage was able to slowly increase in abundance, indicating that populations are presently viable with LGB support. Despite zero egg deposition being predicted for 8 of the first 10 years by the wild population (Figure 7.1), LGB supplementation leads to a low (but non-zero) abundance of wild smolt for all of those years, allowing the population to persist.

A similar pattern was found when 400 simulations were run. With the LGB program in place, egg deposition was projected to increase steadily from the starting value to level off at approximately 500,000 eggs per year after 20 years ($10^{th}$ and $90^{th}$ percentile confidence intervals at approximately 400,000 and 800,000 eggs per year, respectively) (Figure 7.2A). Therefore, it is probable that the population is viable under current conditions with the LGB program, albeit at a small total population size. The probability of extinction remains at zero throughout the projection time period (Figure 7.2B), as does the probability of meeting the recovery target (Figure 7.2C).

***Effect of Marine Mortality***

Presently, the mortality rate of salmon at sea is thought to be the main factor limiting the recovery of iBoF salmon (COSEWIC 2006, Gibson et al. 2004; Trzcinski et al. 2004; Jones et al. 2006). While keeping all other population dynamics parameter values constant, we sequentially reduced at-sea mortality by 2.5% for 4 model runs, both with and without an LGB contribution. This is equivalent to asking: "If current maturity schedules, fecundities, and freshwater productivity for the population remained constant, how would the risk of extinction and the probability of meeting the recovery target change as marine mortality declines?"

For the wild population without an LGB, the population is predicted to go extinct within 10 years at the current at-sea mortality rate (99%; Figure 7.3A). If at-sea mortality is reduced to 96%, there is little appreciable difference, with most simulations going extinct within 20 years. If at-sea mortality is lowered further (94% and 92%, respectively), the population has an 80% chance and a < 2% chance, respectively, of going extinct within 50 years (Figure 7.3A). The population sizes at the higher 3 mortality rates (99%, 96% and 94%) are small, making it very unlikely (< 1% chance) that the population would meet or exceed the recovery target (Figure 7.3B). Marine mortality would have to be reduced to 92% before the population has a > 50% chance of meeting the recovery target, in the absence of the LGB program within 50 years (Figure 7.3B).

When the contribution of the LGB is included, the outcome is very different. Now, there is a zero probability of extinction within 50 years (Figure 7.3C) regardless of the marine mortality rate, because of the individuals raised to maturity in the hatchery environment. This suggests that the number of unfed fry released by the LGB program is large enough to ensure continuous freshwater smolt production, even though the number of adults returning is minimal. Although the population will not go extinct, it has a near-zero probability of meeting the recovery target at the current at-sea mortality rate, suggesting that total adult population size remains small. As marine mortality decreases, the probability of meeting the recovery target increases substantially (Figure 7.3D), yet never reaches a value of 1, which suggests that egg deposition is likely to remain slightly below the recovery target in the absence of changes to other DU population dynamics parameters. In isolation, decreasing marine mortality is not predicted to result in population sizes that remain in excess of the recovery target within the next 50 years.

***Scenario 1: Increased Freshwater Productivity***

This set of scenarios investigated the combined impact of increased freshwater productivity and decreased marine mortality on projected population size, extinction probability, and potential to meet the recovery target, both with and without the LGB. This is equivalent to asking: "How does the population respond if the carrying capacity of freshwater habitat and juvenile survival increases concurrently with declining marine mortality?" Four levels of marine mortality were considered, as well as 4 levels of freshwater productivity, giving a total of 16 combinations. Population size was predicted for all levels of marine mortality (99%, 96%, 94%, and 92%) at each level of freshwater productivity (increases of 0%, 5%, 10%, and 25%, respectively) for a

population without the LGB (Figure 7.4) and with (Figure 7.5), separately. Furthermore, extinction risk (Figure 7.6) and the probability of meeting the recovery target (Figure 7.7) were determined for each of the 16 combinations, with and without the LGB. Selected values are summarized in Table 7.2.

Without the LGB, and at the present marine mortality rate of 99%, increases in freshwater productivity have minimal impact on abundance, with egg deposition trending to zero, regardless of the level of freshwater productivity (Figure 7.4, panels A-D). However, once marine mortality reaches 94%, increasing freshwater productivity begins to affect population viability, given that small viable populations are predicted at a 10% (Figure 7.4, panel K) and a 25% (Figure 7.4, panel L) increase. When marine mortality is low, predicted egg deposition at the end of 50 years is greater by a factor of 5 when freshwater productivity is 25% higher (Figure 7.4, panel P), as compared with current freshwater conditions (Figure 7.4, panel M).

At current marine mortality rates, increasing freshwater productivity has minimal impact on total egg deposition when the wild population is supplemented by the LGB. Predicted egg deposition after 50 years reached a maximum of approximately 600,000 eggs, even when freshwater productivity was increased by 25% (Figure 7.5, panels A-D). However, when marine mortality is low, predicted total egg deposition is an order of magnitude larger, starting at approximately 5 million eggs with current freshwater productivity estimates (Figure 7.5, panel M), and climbing to nearly 12 million eggs if freshwater productivity increases by 25% (Figure 7.5, panel P).

Without the LGB program, there is an extremely high probability of extinction within the next 20 years, regardless of the level of freshwater productivity, provided at-sea mortality remains higher than 96% (Figure 7.6, panels A-H; Table 7.2). When marine mortality is 96%, increases in freshwater productivity extend the time to extinction, rather than reduce the maximum probability of extinction within 50 years (100%; Figure 7.6, panels E-H). This suggests that marine mortality remains the dominant factor controlling the population dynamics. However, once at-sea mortality is reduced to 94%, increasing freshwater productivity significantly lowers the risk of extinction within 50 years, from 60% (Figure 7.6, panel I) to less than 10% (Figure 7.6, panel L). When at-sea mortality is low (92%), increasing freshwater productivity has little impact on the probability of extinction, which remains less than 5% (Figure 7.6, panels M-P; Table 7.2). When the LGB program is in place, the probability of extinction remains zero for all of the 16 combinations (Figure 7.6, panels A-P; Table 7.2).

Without the LGB program, the probability of meeting the recovery target remains zero when marine mortality is 99% or 96%, regardless of the level of freshwater productivity (Figure 7.7, panels A-H; Table 7.2). At 94% marine mortality, the probability of meeting the recovery target jumps from near-zero (Figure 7.7, panel I) to approximately 70% (Figure 7.7, panel L) when freshwater productivity increases from 0% to 25%. When marine mortality is even lower (92%), a 25% increase in freshwater productivity brings the probability of meeting the recovery target close to 100% (Figure 7.7, panel P; Table 7.2). With the LGB program, the population is predicted to have a very high probability of meeting the recovery target once marine mortality drops below 94% (Figure 7.7, panels I-P; Table 7.2). However, the population is predicted to remain consistently in excess of the recovery target only for 1 case, when marine mortality is 92% and freshwater productivity is increased by 25% (Figure 7.7, panel P).

***Scenario 2: Increased Fishing Mortality***

This scenario investigated the opposing effects of increased fishing mortality and decreased marine mortality on projected population size, extinction probability, and potential to meet the recovery target, both with and without the LGB. This is equivalent to asking: “How do low levels

of fishing mortality influence extinction and recovery probabilities under current population dynamics and if populations begin to recover?" Four levels of marine mortality were considered, as well as 4 levels of fishing mortality, giving a total of 16 combinations. Population size, extinction probability, and probability of meeting the recovery targets were predicted for each of the 16 combinations.

Without the LGB program, egg abundance is predicted to trend to zero very quickly when marine mortality is 99%, 96%, or 94%, irrespective of any increases in fishing mortality (Figure 7.8, panels A-L). Small populations are predicted when marine mortality is 92%, regardless of the level of fishing mortality (Figure 7.8, panels M-P). However, increases in fishing pressure reduce the predicted population size after 50 years, from approximately 3 million (Figure 7.8, panel M) to less than half a million eggs (Figure 7.8, panel P), and the $10^{th}$ percentile estimate for the smaller population encompasses zero. Furthermore, the overall trend in population size goes from consistently increasing when fishing mortality goes up by less than 5% (Figure 7.8, panels M-O) to slightly increasing then declining when fishing mortality goes up by 10% (Figure 7.8, panel P).

With the LGB program in place, viable populations are predicted for all combinations of marine mortality and fishing mortality and none of the $10^{th}$ percentile estimates go to zero (Figure 7.9). Modest decreases to the predicted egg deposition occur as fishing mortality goes up, regardless of the level of marine mortality (Figure 7.9). The most notable example being at a marine mortality rate of 94%, where increasing fishing mortality from 0% to 10% caused the predicted median egg deposition to drop from approximately 4 million (Figure 7.9, panel I) to approximately 2 million eggs (Figure 7.9, panel L).

Without the LGB program, there is an extremely high probability of extinction within the next 20 years, regardless of the level of fishing pressure, if at-sea mortality remains higher than 96% (Figure 7.10, panels A-H; Table 7.3). Once at-sea mortality is reduced to 94%, increasing fishing mortality causes the projection to go from a 60% probability of extinction within 50 years (Figure 7.10, panel I) to essentially a 100% probability, after 40 years (Figure 7.10, panel L). When at-sea mortality is low (92%), increasing fishing mortality causes the probability of extinction to climb from < 10% (Figure 7.10, panel M) to approximately 20%, at the end of a 50 year timeframe (Figure 7.10, panel P; Table 7.3). As with the previous scenario, the probability of extinction remains zero for all of the 16 combinations when the LGB program is in place, regardless of the level of fishing mortality (Figure 7.10, panels A-P; Table 7.3).

Fishing mortality has no effect on the probability of meeting the recovery target under the current marine mortality rate. The probability remains zero both with and without the LGB (Figure 7.11, panels A-D; Table 7.3). However, if marine mortality is reduced, fishing mortality has an overall dampening effect on the probability of meeting the recovery target. In the absence of the LGB program, increasing fishing mortality reduces the probability of meeting the recovery target from 60% (Figure 7.11, panel M) to 20% (Figure 7.11, panel P) at the end of the 50 year timeframe, if marine mortality is 92% (Table 7.3). With the LGB program, the probability of meeting the recovery target (assuming 92% marine mortality) is reduced from nearly 100% (Figure 7.11, panel M) to 90% (Figure 7.11, panel P; Table 7.3). This suggests that although fishing mortality is not presently a concern relative to other sources of at-sea mortality, it has the potential to become a limiting factor when at-sea mortality is low, particularly in the absence of the LGB.

***Scenario 3: Downstream Passage Mortality at Hydroelectric Dams (Smolts and Adults)***

Natural in-stream mortality rates can be altered by the presence of hydroelectric generating facilities, whereby turbines can reduce the survival of migrating smolts and adults. This scenario investigated the opposing effects of increased turbine-induced mortality and decreased marine mortality on projected population size, extinction probability, and potential to meet the recovery target, both with and without the LGB. This is equivalent to asking: "Does turbine-induced passage mortality have the potential to limit population recovery if marine mortality rates decline?" Four levels of passage mortality were modeled: 0%, 10%, 25%, and 50%, and were assumed to be equal for smolts and adults (to simplify the presentation). Four levels of marine mortality were considered: 99%, 96%, 94%, and 92%, and population size, extinction probability, and probability of meeting the recovery targets were predicted for each of the 16 combinations.

Without the LGB program, median egg abundance is predicted to go to zero relatively quickly in all but 2 cases, when marine mortality is 92% and turbine mortality is 0% (Figure 7.12, panel M), or when marine mortality is 92% and turbine mortality is 10% (Figure 7.12, panel N). The population is not predicted to be viable if the marine mortality rate is 94% or higher (Figure 7.12, panels A-L). However, when marine mortality is low (92%), it is possible to see the limiting effect of increased turbine mortality on population size. When turbine mortality is 25% or greater, median egg deposition is predicted to go to zero (Figure 7.12, panels O and P). A very low level of egg deposition is expected to be maintained for 50 years when turbine mortality is 10% (Figure 7.12, panel N). When turbine mortality does not influence the population (is 0%), median abundance increases over time to approximately 2 million eggs (Figure 7.12, panel M). However, the $10^{th}$ percentile of the predicted distribution still encompasses zero.

With the LGB program in place, predicted median egg abundance is greater than zero for all combinations of marine and turbine mortality, and none of the $10^{th}$ percentile estimates go to zero (Figure 7.13). However, large median egg abundance at the end of 50 years is only predicted if marine mortality is 94% or less and turbine mortality is 10% or less (Figure 7.13, panels I, J, M, and N). Fifty percent mortality of smolts and adults is enough to reduce the predicted median egg abundance by an order of magnitude, from approximately 6 million eggs (Figure 7.13, panel M) to approximately 800,000 eggs (Figure 7.13, panel P).

The LGB supported population has a zero probability of extinction over a 50 year timeframe for all combinations of marine and turbine mortality (Figure 7.14, panels A-P, Table 7.4). However, the probability of achieving the recovery target varies, reflecting the trade-off between turbine-induced and marine mortality. At a marine mortality rate of 99%, the probability of achieving the recovery target is zero, regardless of the level of turbine-induced mortality (Figure 7.15, panels A-D; Table 7.4). The same result is achieved when turbine mortality is increased by 50% (Figure 7.15, panels D, H, L, and P; Table 7.4). For a population to have a > 50% probability of meeting the recovery target, marine mortality must be 94% or 92%, while turbine-induced mortality is 10% or less (Figure 7.15, panels I, J, M, and N; Table 7.4).

Without the LGB, the same mortality scenario produces dramatically different results. At a marine mortality rate of 99%, the population is insensitive to changing levels of turbine mortality, and is predicted to go extinct within the first 5-10 years (Figure 7.14, panels A-D). In contrast, a population exposed to 92% marine mortality and 0% turbine-induced mortality has a < 10% probability of extinction over the 50 year timeframe (Figure 7.14, panel M; Table 7.4). Tradeoffs exist whereby 2 different combinations of marine mortality and turbine mortality produce near-identical predictions for the probability of extinction. For example, the population is predicted to go extinct within 25 years when at-sea mortality is 96% and turbine mortality is 0% (Figure 7.14,

panel E), or when at-sea mortality is 92% and turbine mortality is 50% (Figure 7.14, panel P). Without the LGB program, the projected population shows a near-zero probability of meeting the recovery target within 50 years at all combinations of marine and turbine mortality except one. When the lowest total mortality combination is modeled (92% at-sea mortality and 0% turbine mortality), the probability of achieving the recovery target rises to 60% by the last year of the simulation (Figure 7.15, panel M; Table 7.6). In nearly all other cases, the probability of meeting the recovery target remains below 10% (Figure 7.15, panels A-L, O, and P).

***Scenario 4: Increased Incidental Juvenile Mortality***

This scenario investigated the opposing effects of increased incidental parr mortality and decreased marine mortality on projected population size, extinction probability, and potential to meet the recovery target, both with and without the LGB. This is equivalent to asking: "Does parr mortality have the potential to reduce population viability irrespective of the carrying capacity of the freshwater environment if marine morality declines?" We simulated a range of increased incidental parr mortality values (0%, 2%, 5%, and 10%) against the range of at-sea mortality rates (as in the above scenarios) to look for interactions.

As in the previous scenarios, median egg abundance is predicted to go to zero when marine mortality is 94% or greater, in the absence of the LGB program (Figure 7.16, panels A-L). However, when marine mortality is 92%, increasing levels of incidental parr mortality lead to marked changes in the predicted median egg abundance. After 50 years, egg abundance had risen to more than 2 million eggs when incidental parr mortality remained unchanged (Figure 7.16, panel M). However, an increase in incidental parr mortality to 10% is enough to cause the predicted median egg abundance to go to zero within 50 years (Figure 7.16, panel P).

With the LGB program in place, viable populations are predicted for all combinations of marine mortality and incidental parr mortality, and none of the $10^{th}$ percentile estimates go to zero (Figure 7.17). However, incidental parr mortality does have an influence on predicted egg abundance. For example, when at-sea mortality is 92%, predicted median abundance after 50 years is greater than 6 million eggs (Figure 7.17, panel M). If the mortality rate of parr increases by 10%, predicted median abundance drops to approximately 4 million eggs (Figure 7.17, panel P).

The LGB supported population has a zero probability of extinction over a 50 year timeframe at all combinations of incidental and at-sea mortality rates (Figure 7.18, panels A-P; Table 7.5). However, the probability of meeting the recovery target is zero for all levels of increased incidental parr mortality when marine mortality is 99% (Figure 7.19, panels A-D; Table 7.5). This suggests that populations are viable, but exist at low sizes when marine mortality is high. For all other mortality combinations (with the LGB), increased incidental mortality does lower the probability of meeting the recovery target, but the overall effect is minimal. Reductions in marine mortality have a much greater effect on the maximum probability of meeting the recovery target, where the probability of meeting the recovery target increases by approximately 20% with each reduction in marine mortality (Figure 7.19, compare panels A, E, I, and M; Table 7.5).

For a population that is not supported by the LGB, the probability of extinction rises to 100% within 8 years when at-sea mortality is 99%, regardless of the level of incidental parr mortality (Figure 7.18, panels A-D; Table 7.5). The general shape of the remaining plots shows the dominant influence of at-sea mortality on extinction risk. However, the maximum probability of extinction, as well as the rate at which the extinction risk increases, is sensitive to the incidental parr mortality rate. When at-sea mortality is 94%, extinction risk climbs from a maximum of approximately 60% (Figure 7.18, panel I) up to 100% (Figure 7.18, panel L) when parr mortality

increases by 10%. Similarly, when marine mortality is 92%, the probability of extinction remains below 10% when incidental parr mortality is low, but triples once parr mortality increases from 5% (Figure 7.18, panel 0) to10% (Figure 7.18, panel P; Table 7.7). The probability of meeting the recovery target is near zero for all interactions except when marine mortality is 92% (Figure 7.19, panels A-L; Table 7.5). At 92%, the probability of meeting the recovery target decreases from a maximum of 60% (Figure 7.19, panel M) to less than 15% (Figure 7.19, panel P) as the incidental parr mortality rate increases from 0% to 10%.

## 8.0 DISCUSSION

All recent survey data from the iBoF indicates that river-specific populations have undergone extreme decline since the 1970's, and are presently very small or extirpated. In rivers without LGB support, all life stages of salmon are found at low abundance, and there is some evidence that population extirpations are ongoing. Supplementation by the Live Gene Bank has increased parr densities in some rivers, but adult returns remain extremely low. The trends analyses indicate a 97% to 99.9% reduction in population size over 3 generations, with basically a zero probability that abundance has increased over this timeframe. Projecting current conditions into the future predicts imminent extinction for the Stewiacke River and the Big Salmon River populations, with no probability of recovery. Neither population is viable at current values of population dynamics parameters in the absence of human intervention.

Live Gene Bank support appears to have maintained, and in some cases increased, observed juvenile densities in some inner Bay of Fundy rivers. Juvenile salmon are found in all supplemented rivers, and their density appears to be dependent on the life stage released back into the wild (which is related to the natural mortality rates of different life stages in the river). For the Big Salmon River, projecting current conditions into the future while accounting for the contribution from the Live Gene Bank predicts small viable populations within 50 years. Population persistence is assured, and the steady input of juveniles from the LGB is enough to offset other sources of mortality and lead to slowly increasing adult abundance. However, given current survival rates, adult abundance is expected to remain well below the recovery target.

Marine mortality is presently limiting population viability and recovery of iBoF salmon. In the Big Salmon River, extinction risk and the probability of recovery changed dramatically as marine mortality declined, even when all other parameters remained constant. For example, a 7% reduction in marine mortality caused the probability of extinction to decline to near-zero over the next 50 years for a population without LGB support. At the same time, there is still only a 50% chance that the wild population could meet the recovery target. If marine mortality remains high, there is no chance of meeting the recovery target. Due to unknown changes in the marine environment, at-sea mortality is at unsustainable rates, resulting in extremely low adult abundances. Unfortunately, identifying and alleviating sources of at-sea mortality during regional recovery efforts is problematic, given that the sources of marine mortality are presently unknown. In the absence of the Live Gene Bank program, remnant populations are expected to extirpate even as research attempts are made to understand and mitigate the causes of increased at-sea mortality.

A relatively low level of LGB support is enough to cause rapid, large changes to extinction risk. This remains true even if freshwater productivity is substantially increased (scenario 1), or if additional sources of mortality (scenarios 2 to 4) affect the population. Additional human-induced mortality does alter the rate and extent of recovery even as marine mortality declines, leading to tradeoffs between different sources of mortality and their combined impact on population viability. However, with the LGB in place, the analyses indicate that these tradeoffs

are negligible, and populations can be maintained even with low levels of mortality caused by human activities.

With respect to the role of low levels of mortality on the probability of extinction or recovery of iBoF salmon, a general pattern emerges from the scenarios presented herein. At the current high levels of at-sea mortality and in the absence of the LGB, low levels of mortality have little impact on the probabilities of recovery (essentially 0%) or extinction (essentially 100%). The rate at which extinction occurs is relatively rapid (under a decade), and although low levels of mortality increase this rate, the increase is small because the rate is so rapid. However, with LGB support, the probability of extinction is low (essentially 0%). Given that wild-exposed juveniles are produced in surplus and the success of the LGB does not depend on adults surviving at sea, the extinction probability does not increase markedly when low levels of human-induced mortality exist in the marine environment.

The above pattern differs in the lower at-sea mortality scenarios analyzed herein. At the lowest at-sea mortality rate, both recovery and extinction probabilities are not very sensitive to low levels of human-induced mortality, although both the size of the recovered population and the recovery rates do decrease as mortality rates increase. The greatest sensitivity to human-induced mortality occurs at the point where at-sea survival rates are beginning to increase and populations are showing signs of recovery. At this point, in the absence of the LGB, both the probability of recovery and the probability of extinction are sensitive to low levels of anthropogenic mortality.

Although the LGB program does greatly reduce the probability of extinction, it is expected that it comes at a cost in terms of both the genetic diversity and the fitness of the populations (O'Reilly and Doyle 2007; Fraser 2008). As such, when the population is showing signs of recovering, it is expected to be advantageous to phase out the LGB to allow natural selection and adaptation to occur in the wild. This would be expected to occur at a time when populations are most sensitive to human-induced mortality. To avoid the risk that any decrease in at-sea mortality could potentially be countered by increased human-induced mortality, it is recommended that this analysis be repeated using the dynamics of the recovering populations in support of decisions about: (1) when to phase out the LGB, and (2) permissible levels of human-induced mortality at this critical stage of recovery.

The increased freshwater production scenario modeled herein relates primarily to remediation of sections of the river that had been impacted by human activities. As with the other scenarios, at-sea mortality must decline before the effects of increased freshwater production become significant. When at-sea mortality is 96%, the PVA predicts a slim possibility of population persistence in the absence of LGB support when freshwater production is increased by 25%. If marine mortality declines further (to 94%), increasing freshwater production by 25% lowers the probability of extinction from about 60% after 50 years to less than 10% after 50 years. For a population subject to 94% marine mortality but with LGB support, the probability of recovery nears 100% if freshwater productivity is increased. This suggests that increasing freshwater productivity could substantially speed up population recovery, and highlights the importance of maintaining healthy freshwater environments for salmon populations to promote recovery.

A fifth scenario not explored in these analyses related to the effects of removing barriers to fish passage. This scenario differs from the increased freshwater productivity scenario above in that the quantity (but not the quality) of habitat would be expected to change. For the life history parameter values analyzed by Trzcinski et al. (2004), the amount of habitat had little effect on the probability of persistence beyond a threshold of about 60,000$m^2$ of habitat (see Figure 3.16 in Trzcinski et al. 2004). This exact threshold estimate is dependent on the model inputs.

However, they also found that population growth rates were very sensitive to the amount of habitat, when populations began to increase in size and density dependence begins to influence population growth rates (Figures 3.9 and 3.10 in Trzcinski et al. 2004). Additionally, the size of the recovered population is increased as the amount of available habitat increases (Figure 3.9 in Trzcinski et al. 2004). Their analyses, together with those provided herein, indicate that if at-sea survival of iBoF salmon improves, barrier removal is a strategy that can increase both the probability of reaching the recovery target and the rate at which the recovery target would be reached. However, as with the effects of other activities assessed herein, present day at-sea survival rates are low enough that they cannot realistically be offset by manipulating the quantity or quality of freshwater habitat.

One limitation to the PVA projection model that may have an effect on the conclusions presented here is the potential reduction in fitness due to domestication selection from the LGB program (Hard 2000). At an individual level, such selection has the potential to reduce population viability and recovery potential by lowering the survival of individuals of LGB origin relative to wild fish. At a population level, any reduction in fitness is likely to make it more difficult to increase freshwater production or to lower marine mortality rates, while at the same time would exacerbate the effects of increased fishing, turbine, or parr mortality on population viability. Domestication selection would have the greatest impact when wild population sizes are small, as they are at present, because individuals of LGB origin would make up a large proportion of the total population size. Further research is needed to quantify the genetic consequences of Live Gene Banking, so that they could be incorporated into the PVA process.

A second limitation to the PVA projection model that influences estimates of extinction risk is the strength of autocorrelation used in the model. Empirical estimates were not available, so a plausible value was assumed. However, if the actual value is higher than that assumed, any estimate of extinction risk would be higher than those presented herein. Long time series (typically 100 years or more) are required in order to estimate autocorrelation with any degree of precision (Lande et al. 2003). Such data are not available in the freshwater or marine environment for iBoF salmon.

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## 10.0 REFERENCES

Amiro, P. 2003. Population status of inner Bay of Fundy Atlantic salmon (*Salmo salar*). Can. Tech. Rep. Fish. Aquat. Sci. 2488.

Amiro, P.G., and E.M. Jefferson. 1996. Status of Atlantic salmon in Salmon Fishing Areas 22 and 23 for 1995, with emphasis on inner Bay of Fundy stocks. DFO Atl. Fish. Res. Doc. 96/134.

Amiro, P.G., A.J.F. Gibson, and K. Drinkwater. 2003. Identification and exploration of some methods for designation of critical habitat for survival and recovery of inner Bay of Fundy Atlantic salmon (*Salmo salar*). DFO Can. Sci. Advis. Sec. Res. Doc. 2003/120.

Beddington, J.R., and J.G. Cooke. 1983. The potential yield of fish stocks. U.N. FAO Fisheries Tech. Paper 242.

CAFSAC. 1991a. Definition of conservation for Atlantic salmon. Can. Atl. Fish. Scient. Adv. Comm. Adv. Doc. 91/15.

CAFSAC. 1991b. Quantification of conservation for Atlantic salmon. Can. Atl. Fish. Scient. Adv. Comm. Adv. Doc. 91/16.

Chaput, G. 2006. Definition and application of conservation requirements for the management of Atlantic salmon (*Salmo salar*) fisheries in eastern Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/021.

Cooper, A.B., and M. Mangel. 1999. The dangers of ignoring metapopulation structure for the conservation of salmonids. Fish. Bull. 97:213-226.

COSEWIC 2006. COSEWIC assessment and update status report on the Atlantic salmon *Salmo salar* (inner Bay of Fundy populations) in Canada, Committee on the Status of Endangered Wildlife in Canada. Ottawa, ON, Canada.

Dadswell, M. 1968. Atlantic salmon (*Salmo salar*) investigations in the Point Wolfe and Upper Salmon rivers in Fundy National Park. Manuscript Report, Limnology Section, Canadian Wildlife Service.

Dennis, B., P. Munholland, and J.M. Scott. 1991. Estimation of growth and extinction parameters for endangered species. Ecol. Mono. 61:115–143.

DFO. 2001. Atlantic salmon Maritime Provinces overview for 2000. DFO Sci. Stock Status Rep. D3-14(2001) (revised).

DFO. 2005. A framework for developing science advice on recovery targets for aquatic species in the context of the *Species at Risk Act*. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2005/054.

DFO. 2006a. Draft Recovery Strategy for the Atlantic salmon (*Salmo salar*), inner Bay of Fundy populations. In *Species at Risk Act* Recovery Strategy Series. November 2006 Draft. Ottawa, ON, Canada.

DFO. 2006b. Science Expert Opinion on Critical Habitat Designation for inner Bay of Fundy Atlantic salmon. DFO Mar. Reg. Exp. Opin. 2006/04.

DFO, 2007. Revised protocol for conducting Recovery Potential Assessments. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2007/039.

Elson, P.F. 1957. Number of salmon needed to maintain stocks. Can. Fish Cultur. 21:19-23.

Gibson, A.J.F. 2006. Population regulation in Eastern Canadian Atlantic salmon (*Salmo salar*) populations. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/016.

Gibson, A.J.F., and P.G. Amiro. 2003. Abundance of Atlantic salmon (Salmo salar) in the Stewiacke River, NS, from 1965 to 2002. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/108.

Gibson, A.J.F., P.G. Amiro, and K.A. Robichaud-LeBlanc. 2003a. Densities of juvenile Atlantic salmon (*Salmo salar*) in inner Bay of Fundy rivers during 2000 and 2002 with reference to past abundance inferred from catch statistics and electrofishing surveys. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/121.

Gibson, A.J.F., R.A. Jones, P.G. Amiro, and J.J. Flanagan. 2003b. Abundance of Atlantic salmon (*Salmo salar*) in the Big Salmon River, NB, from 1951 to 2002. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/119.

Gibson, A.J.F., R.A. Jones, S.F. O'Neil, J.J. Flanagan, and P.G. Amiro. 2004. Summary of monitoring and live gene bank activities for inner Bay of Fundy Atlantic salmon in 2003. DFO Can. Sci. Advis. Sec. Res. Doc. 2004/016.

Goodyear, C.P. 1993. Spawning stock biomass per recruit in fisheries management: foundation and current use; pp. 67-82. In S.J. Smith, J.J. Hunt, and D. Rivard (Eds.). Risk evaluation and biological reference points for fisheries management. Can. Spec. Publ. Fish. Aquat. Sci. 120.

Flanagan, J.J., R.A. Jones, and P. O'Reilly. 2006. A summary and evaluation of Atlantic salmon (*Salmo salar*) smolt monitoring and rotary screw trap activities in the Big Salmon River, 2001-2005. Can. Tech. Rep. Fish. Aquat. Sci. 2646.

Fraser, D.J. 2008. How well can captive breeding programs conserve biodiversity? A review of salmonids. Evol. Appl. 1(4):535-586.

Fraser D.J., M.W. Jones, T.L. McParland, J.A. Hutchings. 2007. Loss of historical immigration and the unsuccessful rehabilitation of extirpated salmon populations. Cons. Genet. 8:527-546.

Hanski, I. 1998. Metapopulation ecology. Oxford University Press, New York, NY, USA.

Hard, J.J. 2000. Genetic interactions between wild and cultured salmon; pp. 8-18. In P. Gallaugher and C. Orr (Eds.). Aquaculture and the protection of wild salmon. Simon Fraser University, Burnaby, BC, Canada.

Hilborn, R. 2001. Risk analysis for salmon spawning reference levels; pp. 177-193 In E. Prevost and G. Chaput (Eds.). Stock, recruitment and reference points, assessment and management of Atlantic salmon. INRA, Paris.

Hilborn, R., and C.J. Walters. 1992. Quantitative fisheries stock assessment: Choice, dynamics and uncertainty. Chapman and Hall, New York, NY, USA.

Hill, M.F., A. Hastings, and L.W. Botsford. 2002. The effects of small dispersal rates on extinction times in structured metapopulation models. Am. Nat. 160:389-402.

Jessop, B.M. 1986. Atlantic salmon (*Salmo salar*) of the Big Salmon River. Can. Tech. Rep. Fish. Aquat. Sci. 1415.

Jessop, B.M. 1975. Investigation of the salmon (*Salmo salar*) smolt migration of the Big Salmon River, New Brunswick, 1966–72. Res. Dev. Br., Fisheries and Marine Service, Department of the Environment, Tech. Rpt. Series No. MAR/T-75-1, 57.

Jones, R.A., L. Anderson, J.J. Flanagan, and T. Goff. 2006. Assessment of Atlantic salmon stocks in southern and western New Brunswick, an update to 2005. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/025.

Lande, R., S. Engen, and B.-E. Saether. 2003. Stochastic population dynamics in ecology and conservation. Oxford Series in Ecology and Evolution. Oxford University Press, Oxford, UK.

Legault, C.M. 2005. Population viability analysis of Atlantic salmon in Maine, USA. Trans. Am. Fish. Soc. 134:549-562.

Marshall, T.L., G.J. Chaput, P.G. Amiro, D.K. Cairns, R.A. Jones, S.F. O'Neil, and J.A. Ritter. 1999. Assessments of Atlantic salmon stocks of the Maritimes Region, 1998. DFO Can. Stock Assess. Sec. Res. Doc. 99/25.

McCarthy, M.A., H.P. Possingham, J.R. Day, and A. J. Tyre. 2001. Testing the accuracy of population viability analysis. Conserv. Biol. 15:1030-1038.

Myers, R.A., A.A. Rosenberg, P.M. Mace, N. Barrowman, and V.R. Restrepo. 1994. In search of the thresholds of recruitment overfishing. ICES J. Mar. Sci. 51:191-205.

National Recovery Team. 2002. National Recovery Strategy for inner Bay of Fundy Atlantic salmon (*Salmo salar*) populations. FINAL DRAFT: National Recovery Strategy, Recovery of Nationally Endangered Wildlife (RENEW). Ottawa, ON, Canada.

O'Reilly, P.T., and R.W. Doyle. 2007. Live gene banking of endangered populations of Atlantic salmon; pp. 425-469. In E. Verspoor, L. Stradmeyer, and J. Nielsen (Eds.). The Atlantic salmon: Genetics, conservation and management. Blackwell, London, UK.

Reed, J.M., L.S. Mills, J.B. Dunning, E.S. Menges, K.S. McKelvey, R. Frye, S.R. Beissinger, M.-C. Anstett, and P. Miller. 2002. Emerging issues in Population Viability Analysis. Conserv. Biol. 16:7-19.

Shelton, P.A., B. Best, A. Cass, C. Cyr, D. Duplisea, J. Gibson, M. Hammill, S. Khwaja, M. Koops, K. Martin, R. O'Boyle, J. Rice, A. Sinclair, K. Smedbol, D. Swain, L. Velez-Espino, and C. Wood. 2007. Assessing recovery potential: Long-term projections and their implications for socio-economic analysis. DFO Can. Sci. Advis. Sec. Res. Doc. 2007/045.

Trzcinski, M.K., A.J.F. Gibson, P.G. Amiro, and R.G. Randall. 2004. Inner Bay of Fundy Atlantic salmon critical habitat case study. DFO Can. Sci. Advis. Sec. Res. Doc. 2004/114.

Verspoor, E., M. O'Sullivan, A.L. Arnold, D. Knox, and P.G. Amiro. 2002. Restricted matrilineal gene flow and regional differentiation among Atlantic salmon (*Salmo salar* L.) populations within the Bay of Fundy, Eastern Canada. Heredity 89:465-472.

Table 2.1. Summary of the adult Atlantic salmon counts at the White Rock fish ladder on the Gaspereau River, N.S., from 1997 to 2007.

| | | | Year | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Origin | Size | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007[a] |
| Released into river: | Wild | Large | 5 | 6 | 11 | 3 | 6 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Small | 30 | 9 | 1 | 7 | 7 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Hatchery | Large | 2 | 10 | 13 | 4 | 10 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Small | 22 | 42 | 0 | 30 | 5 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retained for broodstock: | Wild | Large | 7 | 3 | 14 | 4 | 14 | 0 | 2 | 0 | 0 | 0 | 0 |
| | | Small | 23 | 7 | 2 | 14 | 6 | 8 | 2 | 6 | 1 | 1 | 1 |
| | Hatchery | Large | 5 | 2 | 0 | 9 | 3 | 4 | 0 | 1 | 0 | 1 | 0 |
| | | Small | 8 | 20 | 0 | 5 | 6 | 2 | 3 | 7 | 1 | 2 | 1 |
| Total count: | | Large | 19 | 21 | 38 | 20 | 33 | 4 | 2 | 1 | 1 | 1 | 0 |
| | | Small | 83 | 78 | 3 | 56 | 24 | 10 | 5 | 13 | 1 | 3 | 2 |
| Total count all sizes: | | | 102 | 99 | 41 | 76 | 57 | 14 | 7 | 14 | 2 | 4 | 2 |
| % | | counted | 74 | 56 | 30 | 16 | 24 | 8 | 5 | 8 | 1 | 2 | 1 |
| Conservation | | escapement | 43 | 42 | 15 | 9 | 18 | 0 | 0 | 0 | 0 | 0 | 0 |

[a]Excludes two reconditioned LGB-released male salmon.

Table 2.2. Counts of adult Atlantic salmon by stream-side observation and dive surveys in the Big Salmon River from 1988-2007. Data sources and spawning escapement estimates from the source documents are also provided.

| Year | Date | Count technique | Count | Escapement estimate | Reference | Notes |
|---|---|---|---|---|---|---|
| 1988 | Fall | diver observations | 300-400 fish | 350 | Amiro et. al. (1989) | |
| 1989 | Fall | diver observations | 975 fish | 975 | O'Neil et. al (1989) | |
| 1990 | Oct. 18 | diver observations | 64 small / 169 large | 235 | Amiro et. al. (1991) | a |
| 1991 | Aug. 16 | diver observations | 49 small / 115 large | - | Amiro (1992) | |
| 1991 | Sept. 12 / 17 | diver observations | 105 small / 151 large | 300 | Amiro (1992) | b |
| 1992 | Aug. 21 / Sept. 29 | diver observations | 150 fish | 150 | Amiro et. al. (1993) | |
| 1993 | Aug. 27 | stream-side obs. | 165 fish | 300 | Cutting et. al. (1994) | |
| 1994 | Sept. 27 | stream-side obs. | 225 fish | 225 | Amiro and Longard (1995) | c |
| 1995 | Aug. 22 | stream-side obs. | 10 small / 23 large | - | Amiro and Jefferson (1996) | d,e,h |
| 1995 | Sept. 26 | stream-side obs. | 18 small / 53 large | 110 | Amiro and Jefferson (1996) | f |
| 1996 | | stream-side obs. | 100-150 | 125 | Amiro and Jefferson (1997) | |
| 1997 | | stream-side obs. | 50 fish | 50 | DFO SSR D3-12 (1998) | |
| 1998 | | stream-side obs. | 25-50 fish | 38 | Marshall et. al. (1999) | |
| 2000 | Oct. 16-18 | diver observations | 23 small / 5 large | 41 | DFO SSR D3-14 (2001) | g,h |
| 2001 | Oct. 22-23 | diver observations | 12 small / 8 large | 30 | DFO SSR D3-14 (2002) | g,h |
| 2002 | Aug. 27 / Sept. 3 | diver observations | 16 small / 5 large | 31 | DFO SSR D3-14 (2003) | g,h |
| 2003 | Oct. 2 | diver observations | 10 small / 2 large | 21 | Gibson et al. (2004) | i |
| 2004 | Oct. 20 | diver observations | 4 small / 5 large | 16 | Jones et al. (2006) | j |
| 2005 | Sept. 7-8, 14 | diver observations | 23 small / 11 large | 60 | Jones et al. (2006) | j |
| 2006 | Aug. 30, Sept. 5-6 | diver observations | 34 small / 10 large | 77 | Unpublished | j |
| 2007 | Aug. 1, Sept. 5, Oct. 1 | diver observations | 26 small / 2 large | 47 | Unpublished | k |

Notes: a - high water (count is a minimum estimate).
b - complete river surveyed except 1 pool.
c - diver observations on Oct. 19 indicated escapements could have been less than the 225.
d - 15 pools surveyed representing 74% of the total river based on the 1991 complete river survey.
e - streamside survey on Oct. 19 indicated no new fish in the river.
f - counts were hindered by high water, estimated number is based on 2 partial surveys and a count for Catt and Rody pools.
g - details can be found in Appendix 3.
h - adjusted estimate = counts / (proportion of river surveyed) / (estimated observation rate). Amiro and Jefferson (1996).
i - mark recapture estimate (Gibson et al. 2004).
j - borrowed observation rate (0.57) from '2003' survey (Gibson et al. 2004).
k - mark recapture estimate from 2007 survey data.

Table 2.3. Annual means and standard deviations (s.d.) of age-0, age-1, and age-2 Atlantic salmon densities (number per $100m^2$) in the Big Salmon River, N.B., estimated during electrofishing surveys between 1968 to 2007. "N" is the number of sites electrofished in each year. Asterisks indicate years when juvenile density estimates may have been affected by juvenile stocking and may not be indicative of wild production for that life stage.

| | | Age-0 | | Age-1 | | Age-2 | |
|---|---|---|---|---|---|---|---|
| Year | N | mean | s.d. | mean | s.d. | mean | s.d. |
| 1968 | 3 | 16.9 | 19.5 | 14.7* | 4.8 | 11.8 | 6.1 |
| 1970 | 4 | 23.6 | 30.7 | 1.2* | 2.4 | 6.0 | 3.5 |
| 1971 | 5 | 6.4* | 8.1 | 11.1 | 14.2 | 4.2* | 2.9 |
| 1972 | 5 | 11.5 | 6.0 | 3.2* | 3.6 | 4.1 | 4.7 |
| 1973 | 5 | 40.0 | 41.0 | 4.5* | 3.0 | 3.0* | 2.4 |
| 1982 | 3 | 68.5 | 70.3 | 47.8 | 30.9 | 10.1 | 6.9 |
| 1989 | 5 | 15.7 | 11.0 | 12.0 | 8.8 | 2.7 | 3.0 |
| 1990 | 5 | 39.3 | 40.2 | 12.0* | 8.5 | 1.8 | 1.9 |
| 1991 | 4 | 17.1 | 14.7 | 14.0* | 9.1 | 2.8* | 4.2 |
| 1992 | 4 | 18.1 | 12.0 | 13.3* | 8.6 | 1.7* | 2.3 |
| 1993 | 3 | 2.3 | 1.4 | 12.5 | 14.3 | 4.4* | 4.0 |
| 1994 | 4 | 10.4 | 11.9 | 6.7* | 3.3 | 3.3 | 3.5 |
| 1995 | 4 | 21.8 | 18.4 | 6.4* | 7.4 | 2.0* | 1.3 |
| 1996 | 5 | 49.2 | 38.6 | 10.7 | 5.5 | 0.5* | 0.6 |
| 1997 | 5 | 23.7* | 19.5 | 6.6 | 10.3 | 1.4 | 0.9 |
| 1998 | 5 | 3.1 | 2.8 | 13.2* | 15.5 | 4.4 | 4.7 |
| 1999 | 5 | 7.8 | 13.5 | 3.9 | 4.5 | 2.2* | 3.0 |
| 2000 | 5 | 7.5 | 12.3 | 3.5 | 4.0 | 0.2 | 0.5 |
| 2001 | 5 | 11.1* | 20.6 | 6.8 | 5.7 | 1.2 | 2.7 |
| 2002 | 5 | 16.9* | 21.0 | 12.7* | 8.3 | 0.6 | 0.7 |
| 2003 | 5 | 28.0* | 43.8 | 12.8* | 12.5 | 1.8* | 1.7 |
| 2004 | 5 | 27.6* | 34.9 | 15.4* | 19.2 | 1.1* | 0.6 |
| 2005 | 5 | 28.9* | 38.0 | 8.3* | 5.2 | 1.6* | 2.2 |
| 2006 | 4 | 19.4* | 13.0 | 14.6* | 7.9 | 1.3* | 0.8 |
| 2007 | 5 | 28.7* | 29.5 | 24.7* | 17.6 | 2.5* | 2.8 |

Table 2.4. Summary statistics for parr densities (number per 100m$^2$), all age classes combined, in the Upper Salmon River, N.B., estimated by electrofishing.

| Year | Number of Sites | Minimum | 1st Quartile | Median | 3rd Quartile | Maximum | Mean | Std Dev. |
|---|---|---|---|---|---|---|---|---|
| 1984 | 6 | 13.53 | 30.83 | 33.66 | 34.28 | 39.19 | 30.74 | 8.93 |
| 1985 | 6 | 12.50 | 26.17 | 42.45 | 67.48 | 136.00 | 54.99 | 45.13 |
| 1987 | 6 | 12.40 | 28.78 | 49.57 | 56.99 | 62.00 | 42.48 | 20.20 |
| 1993 | 2 | 14.00 | 15.12 | 16.24 | 17.36 | 18.48 | 16.24 | 3.17 |
| 1994 | 2 | 10.93 | 11.26 | 11.59 | 11.92 | 12.26 | 11.59 | 0.94 |
| 1995 | 2 | 5.63 | 5.68 | 5.73 | 5.79 | 5.84 | 5.73 | 0.15 |
| 1996 | 2 | 3.12 | 3.34 | 3.56 | 3.78 | 4.00 | 3.56 | 0.62 |
| 1997 | 2 | 1.07 | 2.24 | 3.40 | 4.57 | 5.74 | 3.40 | 3.30 |
| 1999 | 2 | 0.27 | 0.76 | 1.24 | 1.73 | 2.22 | 1.24 | 1.38 |
| 2000 | 2 | 0.48 | 0.88 | 1.27 | 1.67 | 2.07 | 1.27 | 1.12 |
| 2001 | 6 | 0.00 | 0.50 | 1.11 | 3.97 | 5.93 | 2.23 | 2.53 |
| 2002 | 5 | 0.00 | 0.00 | 0.00 | 0.67 | 1.44 | 0.42 | 0.64 |
| 2003 | 6 | 0.00 | 0.00 | 0.00 | 0.00 | 0.56 | 0.093 | 0.23 |
| 2005 | 6 | 0.00 | 0.00 | 0.00 | 0.24 | 0.33 | 0.11 | 0.17 |
| 2006 | 6 | 1.09 | 2.71 | 5.53 | 9.14 | 11.54 | 5.97 | 4.20 |

Table 2.5. Summary of the number of adult salmon observed in recent snorkel surveys in Point Wolfe River, N.B., and Upper Salmon River, N.B. Tagged salmon are known to have been released as adults.

| | | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|
| Point Wolfe River | Grilse | | | | 1 | 1 |
| | Salmon | | 2 | | | |
| Upper Salmon River | Grilse | 3 | 1(tag) | | 1 (tag) | |
| | Salmon | | | | | 1 |

Table 2.6. Summary statistics for parr densities (number per 100m$^2$), all age classes combined, in the Point Wolfe River, N.B., estimated by electrofishing.

| Year | Number of Sites | Minimum | 1st Quartile | Median | 3rd Quartile | Maximum | Mean | Std Dev. |
|---|---|---|---|---|---|---|---|---|
| 1983 | 2 | 5.00 | 9.00 | 13.00 | 17.00 | 21.00 | 13.00 | 11.31 |
| 1984 | 6 | 0.57 | 1.68 | 2.43 | 3.43 | 15.56 | 4.36 | 5.58 |
| 1985 | 2 | 4.41 | 5.31 | 6.21 | 7.10 | 8.00 | 6.21 | 2.54 |
| 1987 | 5 | 16.07 | 25.64 | 31.00 | 39.32 | 81.94 | 38.79 | 25.55 |
| 1988 | 5 | 7.58 | 14.07 | 15.58 | 28.79 | 29.86 | 19.18 | 9.75 |
| 1989 | 5 | 1.23 | 4.23 | 4.48 | 6.61 | 33.48 | 10.01 | 13.26 |
| 1990 | 5 | 2.03 | 3.42 | 5.79 | 6.14 | 11.49 | 5.77 | 3.62 |
| 1991 | 5 | 11.15 | 14.99 | 19.23 | 29.54 | 48.48 | 24.68 | 14.97 |
| 1992 | 5 | 3.19 | 5.31 | 9.55 | 17.38 | 26.42 | 12.37 | 9.55 |
| 1993 | 5 | 1.15 | 4.14 | 15.05 | 43.15 | 55.56 | 23.81 | 24.29 |
| 1994 | 5 | 4.17 | 5.01 | 5.36 | 11.19 | 13.64 | 7.87 | 4.26 |
| 1995 | 5 | 0.25 | 2.20 | 2.69 | 15.00 | 17.24 | 7.48 | 7.98 |
| 1996 | 5 | 0.34 | 0.60 | 2.86 | 3.22 | 5.00 | 2.40 | 1.94 |
| 1997 | 5 | 0.00 | 0.00 | 0.97 | 6.03 | 18.97 | 5.19 | 8.10 |
| 1999 | 5 | 0.00 | 0.00 | 0.17 | 0.34 | 0.34 | 0.17 | 0.20 |
| 2000 | 5 | 0.37 | 0.50 | 0.51 | 0.78 | 1.11 | 0.65 | 0.30 |
| 2001 | 6 | 0.00 | 0.09 | 1.08 | 11.29 | 21.62 | 6.37 | 9.34 |
| 2002 | 6 | 0.00 | 0.22 | 0.98 | 1.53 | 5.56 | 1.53 | 2.08 |
| 2003 | 6 | 0.00 | 0.71 | 1.65 | 2.36 | 5.00 | 1.88 | 1.79 |
| 2004 | 5 | 0.00 | 1.71 | 2.93 | 3.05 | 6.99 | 2.94 | 2.58 |
| 2005 | 6 | 0.71 | 2.59 | 3.24 | 4.35 | 5.08 | 3.23 | 1.58 |
| 2006 | 6 | 0.00 | 0.09 | 0.58 | 0.84 | 2.67 | 0.78 | 1.00 |

Table 4.1. Data used to estimate life history parameters for Atlantic salmon in the Big Salmon River, N.B., taken from Trzcinski et al. (2004). Actual data are provided in Jessop (1975), Jessop (1986), Gibson et al. (2003b), and Gibson et al. (2004).

| Data set | Years available |
|---|---|
| juvenile electrofishing | 1968, 1970, 1971, 1972, 1973, 1982, 1989 to 2003 |
| redd counts | 1996 to 2002 |
| streamside obs. and dive counts for adults | 1988 to 2003 |
| recreational fishing catch and effort | 1951 to 1990 (1964 to 1990 used herein) |
| fence counts for adults | 1964 to 1973 |
| fence counts for smolts | 1966 to 1971 |
| Mark-recapture estimates for smolts | 2001 to 2003 |
| adult sex, age and previous spawning data | 1964 to 1973, 2001 to 2003 |
| smolt age data | 1966 to 1972, 2001 to 2003 |

Table 4.2. Parameter maximum likelihood estimates (MLE) obtained from 3 models fit to the Big Salmon River Atlantic salmon data. In the "base" model, estimated life history parameters are assumed to be constant through time. In the "freshwater" model, the estimated life history parameters for the freshwater component differ between the pre-1990 and 1990 and later time periods, while the parameters for the marine component are assumed constant through time. In the "marine" model, the estimated life history parameters for the marine component differ between the pre-1990 and 1990 and later time periods, while the parameters for the freshwater component are assumed constant through time. Standard errors (SE) are obtained using the delta method under the assumption of asymptotic normality (reproduced from Trzcinski et al. 2004).

| | Model | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Base | | Freshwater | | | | Marine | | | |
| | | | pre-1990 | | 1990 and later | | pre-1990 | | 1990 and later | |
| | MLE | SE | MLE | SE | MLE | SE | MLE | SE | MLE | SE |
| Sampling coefficients: | | | | | | | | | | |
| electrofishing q | 2.79E+03 | 8.19E+02 | 2.27E+03 | 4.66E+02 | | | 2.99E+03 | 2.93E+02 | | |
| stream and dive count q | 3.57E-01 | 5.97E-02 | 4.78E-01 | 7.55E-02 | | | 5.13E-01 | 8.51E-02 | | |
| redd count q | 1.46E-01 | 5.76E-02 | 3.43E-01 | 1.31E-01 | | | 3.49E-01 | 1.38E-01 | | |
| fishing q (small salmon) | -9.61E+00 | 7.38E-02 | -9.63E+00 | 7.59E-02 | | | -9.60E+00 | 7.61E-02 | | |
| fishing q (large salmon) | -9.59E+00 | 9.18E-02 | -9.58E+00 | 9.36E-02 | | | -9.48E+00 | 9.51E-02 | | |
| Life history parameters: | | | | | | | | | | |
| egg mortality | 9.65E-01 | 1.07E-02 | 9.80E-01 | 4.09E-03 | 9.61E-01 | 8.98E-03 | 9.59E-01 | 3.15E-05 | | |
| Beverton-Holt $\alpha$ | 5.00E-01 | 6.54E-02 | 5.15E-01 | 3.16E-02 | 9.09E-01 | 1.11E-01 | 6.29E-01 | 7.20E-02 | | |
| Beverton-Holt $R_0$ | 7.04E+02 | 1.42E+03 | 4.86E+01 | 2.09E+01 | 5.59E+02 | 6.74E+02 | 8.71E+01 | 3.12E+01 | | |
| parr mortality | 6.23E-01 | 6.32E-02 | 2.35E-01 | 7.60E-02 | 8.53E-01 | 1.68E-02 | 6.13E-01 | 3.38E-02 | | |
| sea mortality (immature) | 8.12E-01 | 4.38E-02 | 7.15E-01 | 4.45E-02 | | | 8.29E-01 | 2.56E-02 | 9.70E-01 | 1.42E-02 |
| sea mortality (post-spawn) | 5.02E-01 | 9.20E-03 | 5.00E-01 | 9.22E-03 | | | 4.95E-01 | 9.88E-03 | 6.43E-01 | 2.52E-02 |
| prob. smolt age-2 | 2.90E-01 | 3.80E-02 | 4.41E-01 | 2.61E-02 | | | 2.96E-01 | 2.02E-02 | | |
| prob. smolt age-3 | 9.09E-01 | 1.51E-02 | 9.51E-01 | 6.09E-03 | | | 9.11E-01 | 9.63E-03 | | |
| prob. maturing 1SW | 2.87E-01 | 8.31E-02 | 1.22E-01 | 2.38E-02 | | | 2.63E-01 | 5.32E-02 | 8.40E-01 | 3.86E-01 |
| smolt sex ratio | 2.77E-01 | 7.90E-03 | 2.77E-01 | 7.91E-03 | | | 2.78E-01 | 7.90E-03 | | |
| Population initialization: | | | | | | | | | | |
| number of eggs (1959) | 7.28E+06 | 2.19E+06 | 1.61E+07 | 3.60E+06 | | | 8.40E+06 | 1.89E+06 | | |
| number of eggs (1960) | 4.62E+06 | 2.02E+06 | 1.78E+07 | 6.08E+06 | | | 5.63E+06 | 1.82E+06 | | |
| number of eggs (1961) | 2.95E+06 | 7.21E+05 | 6.77E+06 | 1.58E+06 | | | 3.33E+06 | 6.30E+05 | | |
| number of eggs (1962) | 4.13E+06 | 1.01E+06 | 4.40E+06 | 8.93E+05 | | | 4.65E+06 | 5.87E+05 | | |
| number of eggs (1963) | 6.54E+06 | 2.59E+06 | 2.98E+06 | 7.70E+05 | | | 7.52E+06 | 1.07E+06 | | |
| number of eggs (1964) | 1.03E+07 | 6.08E+05 | 9.95E+06 | 5.84E+05 | | | 1.00E+07 | 6.01E+05 | | |
| Objective function value: | 3399.9 | | 3210.5 | | | | 3359.0 | | | |

Table 5.1. Constants used in the PVA projection model for the wild and the LGB components of the population.

| | Name | Stage | Wild | LGB |
|---|---|---|---|---|
| Life history parameter | | | | |
| Constants | Fecundity | adult, small<br>adult, large | 3233<br>5541 | 3233<br>5541 |
| | Max parr age | | 3 | 3 |
| | Min age of smoltification<br>Max age of smoltification | | 2<br>4 | 2<br>4 |
| | Min number of years as immature<br>Max number of years as immature | | 1<br>2 | 1<br>2 |
| | Min age of first reproduction | | 3 | 3 |
| | Max number of previous spawning | | 5 | 0 |
| | Max age | | 10 | 6 |
| | Max annual smolt collection (for LGB) | | | 150 |
| | Collection efficiency (for LGB) | | | 0.1 |
| | Freshwater and Marine Autocorrelation | | 0.1 | 0.1 |

Table 6.1. Conservation spawner requirements for inner Bay of Fundy Atlantic salmon (from DFO 2006b).

| | | | | Number of salmon | | |
|---|---|---|---|---|---|---|
| SFA | River | Rearing Units (100 $m^2$) | Egg Requirement | Small | Large | Total |
| 22 | Apple | 2,111 | 506,640 | 125 | 47 | 171 |
| | Bass (Col.) | 696 | 167,040 | 41 | 15 | 56 |
| | Chiganois | 3,369 | 808,560 | 199 | 74 | 273 |
| | Cornwallis | 1,706 | 409,440 | 182 | 44 | 226 |
| | Debert | 3,499 | 839,760 | 206 | 77 | 284 |
| | Diligent | 335 | 80,400 | 20 | 7 | 27 |
| | Economy | 2,386 | 572,640 | 141 | 53 | 193 |
| | Folly | 2,896 | 695,040 | 171 | 64 | 235 |
| | Gaspereau[1] | 3,856 | 925,440 | 412 | 99 | 511 |
| | Gaspereau[2] | 3,325 | 798,216 | 85 | 127 | 212 |
| | Great Village | 2,587 | 620,880 | 153 | 57 | 210 |
| | Harrington | 629 | 150,960 | 37 | 14 | 51 |
| | Kennetcook | 3,976 | 954,240 | 235 | 88 | 322 |
| | Maccan | 8,228 | 1,974,720 | 485 | 182 | 667 |
| | North (Col.) | 4,485 | 1,076,400 | 265 | 99 | 364 |
| | Parrsboro | 705 | 169,200 | 42 | 16 | 57 |
| | Portapique | 3,309 | 794,160 | 195 | 73 | 268 |
| | R. Hebert | 2,282 | 547,680 | 135 | 50 | 185 |
| | Salmon (Col.) | 13,468 | 3,232,320 | 795 | 297 | 1,092 |
| | Shubenacadie | 10,340 | 2,481,600 | 610 | 228 | 838 |
| | St. Croix (Hants) | 4,283 | 1,027,920 | 253 | 95 | 347 |
| | Stewiacke | 13,086 | 3,140,640 | 772 | 289 | 1,061 |
| | Tantramar | | | | | |
| 23 | Big Salmon | 9,093 | 2,182,320 | 280 | 420 | 700 |
| | Point Wolfe | | | 139 | 63 | 202 |
| | Petitcodiac | 28,150 | 6,756,000 | 1688 | 101 | 1,789 |
| | Shepody | | | | | |
| | Upper Salmon | | | 60 | 29 | 89 |
| | Totals[3]: | 124,944 | 29,986,776 | 7,314 | 2,609 | 9,919 |

1. The whole of the Gaspereau River including areas upstream of the Lanes Mill fish ladder and Trout River Pond (from O'Connell et al. 1997).
2. Gaspereau River downstream of the Lanes Mills fish ladder and Trout River Pond.
   - Present management restricts salmon to the downstream areas to avoid turbine mortality associated with downstream passage in other parts of the watershed.
   - From Amiro and Jefferson (1996); authors used an updated set of biological characteristics so the ratios of the egg requirement to the area using the 2 methods are not the same).
3. Area downstream of Lanes Mills on Gaspereau River used for totals.

Table 7.1. Estimates of the current population dynamics parameters for cohorts from the Live Gene Bank (LGB) program for inner Bay of Fundy salmon. The values were used as constants.

| Parameter | | Estimate |
|---|---|---|
| egg mortality (hatchery) | $M_{LGB}^{Egg}$ | 0.139 |
| Transfer survival (of unfed fry) | $T_{LGB}^{fry}$ | 0.107 |
| Transfer mortality (of smolts) | $M_{LGB}^{Smolt}$ | 0.100 |
| Adult mortality (hatchery) | $M_{LGB}^{Adult}$ | 0.010 |
| prob. maturing 1SW | $m_1^{LGB}$ | 0.955 |

Table 7.2. Summary of the probability of meeting the recovery target and the probability of extinction at year 10 and year 50 for Scenario 1 (declining marine mortality and increasing freshwater productivity (FWP)) for a population with (Wild + LGB) and without (Wild Only) LGB supplementation.

| | | After 10 Years | | | | After 50 Years | | | |
|---|---|---|---|---|---|---|---|---|---|
| Marine Mortality | Increase in FWP | Prob. of Extinction | | Prob. of Meeting Recovery Target | | Prob. of Extinction | | Prob. of Meeting Recovery Target | |
| % | % | Wild Only | Wild + LGB | Wild Only | Wild + LGB | Wild Only | Wild + LGB | Wild Only | Wild + LGB |
| 99 | 0 | 100 | 0.0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 5 | 100 | 0.0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 10 | 100 | 0.0 | 0 | 0 | 100 | 0 | 0 | 0.4 |
| 99 | 25 | 99.6 | 0.0 | 0 | 0 | 100 | 0 | 0 | 0.6 |
| 96 | 0 | 43.2 | 0.0 | 0 | 0 | 100 | 0 | 0 | 38.6 |
| 96 | 5 | 37.6 | 0.0 | 0 | 0 | 100 | 0 | 0 | 49 |
| 96 | 10 | 29.8 | 0.0 | 0 | 0 | 99.8 | 0 | 0 | 58.8 |
| 96 | 25 | 15.6 | 0.0 | 0 | 0.8 | 90.8 | 0 | 0.4 | 78.8 |
| 94 | 0 | 9.2 | 0.0 | 0 | 0.8 | 61.4 | 0 | 4.4 | 81.2 |
| 94 | 5 | 6.6 | 0.0 | 0 | 1.2 | 34.4 | 0 | 12.8 | 87.2 |
| 94 | 10 | 5.4 | 0.0 | 0 | 1.2 | 15.6 | 0 | 27.8 | 91 |
| 94 | 25 | 3.4 | 0.0 | 0 | 5.8 | 1.6 | 0 | 72 | 98.2 |
| 92 | 0 | 3.2 | 0.0 | 0 | 1.6 | 2.6 | 0 | 62.2 | 95.6 |
| 92 | 5 | 2.6 | 0.0 | 0 | 4 | 1.6 | 0 | 78 | 98.2 |
| 92 | 10 | 1.2 | 0.0 | 0 | 6.6 | 1.6 | 0 | 84.4 | 99 |
| 92 | 25 | 0.4 | 0.0 | 1 | 18.4 | 1.4 | 0 | 97 | 99.8 |

Table 7.3. Summary of the probability of meeting the recovery target and the probability of extinction at year 10 and year 50 for Scenario 2 (declining marine mortality and increasing fishing mortality) for a population with (Wild + LGB) and without (Wild Only) LGB supplementation.

| | | After 10 Years | | | | After 50 Years | | | |
|---|---|---|---|---|---|---|---|---|---|
| Marine Mortality | Increase in fishing mortality | Prob. of Extinction | | Prob. of Meeting Recovery Target | | Prob. of Extinction | | Prob. of Meeting Recovery Target | |
| % | % | Wild Only | Wild + LGB | Wild Only | Wild + LGB | Wild Only | Wild + LGB | Wild Only | Wild + LGB |
| 99 | 0 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 2.5 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 5 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 10 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 96 | 0 | 43.2 | 0 | 0 | 0 | 100 | 0 | 0 | 38.6 |
| 96 | 2.5 | 49.6 | 0 | 0 | 0 | 100 | 0 | 0 | 32.4 |
| 96 | 5 | 56.2 | 0 | 0 | 0 | 100 | 0 | 0 | 28.8 |
| 96 | 10 | 62.8 | 0 | 0 | 0 | 100 | 0 | 0 | 19.2 |
| 94 | 0 | 9.2 | 0 | 0 | 0.8 | 61.4 | 0 | 4.4 | 81.2 |
| 94 | 2.5 | 11 | 0 | 0 | 0.6 | 77.8 | 0 | 1.2 | 77.8 |
| 94 | 5 | 14.2 | 0 | 0 | 0.2 | 92.4 | 0 | 0.2 | 73.8 |
| 94 | 10 | 20.2 | 0 | 0 | 0 | 99 | 0 | 0 | 63.4 |
| 92 | 0 | 3.2 | 0 | 0 | 1.6 | 2.6 | 0 | 62.2 | 95.6 |
| 92 | 2.5 | 3.8 | 0 | 0 | 1.6 | 4.8 | 0 | 50.6 | 94.4 |
| 92 | 5 | 4.2 | 0 | 0 | 1.4 | 7.2 | 0 | 39.6 | 92.4 |
| 92 | 10 | 5.4 | 0 | 0 | 1 | 18.8 | 0 | 19.4 | 89.2 |

Table 7.4. Summary of the probability of meeting the recovery target and the probability of extinction at year 10 and year 50 for Scenario 3 (declining marine mortality and increasing turbine mortality for smolts and adults) for a population with (Wild + LGB) and without (Wild Only) LGB supplementation.

| | | After 10 Years | | | | After 50 Years | | | |
|---|---|---|---|---|---|---|---|---|---|
| Marine Mortality | Increase in turbine mortality | Prob. of Extinction | | Prob. of Meeting Recovery Target | | Prob. of Extinction | | Prob. of Meeting Recovery Target | |
| % | % | Wild Only | Wild + LGB | Wild Only | Wild + LGB | Wild Only | Wild + LGB | Wild Only | Wild + LGB |
| 99 | 0 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 10 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 25 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 50 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 96 | 0 | 43.2 | 0 | 0 | 0 | 100 | 0 | 0 | 38.6 |
| 96 | 10 | 62.8 | 0 | 0 | 0 | 100 | 0 | 0 | 19.4 |
| 96 | 25 | 86.8 | 0 | 0 | 0 | 100 | 0 | 0 | 5.2 |
| 96 | 50 | 99.6 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 94 | 0 | 9.2 | 0 | 0 | 0.8 | 61.4 | 0 | 4.4 | 81.2 |
| 94 | 10 | 20.2 | 0 | 0 | 0 | 99 | 0 | 0 | 63.6 |
| 94 | 25 | 48 | 0 | 0 | 0 | 100 | 0 | 0 | 26.2 |
| 94 | 50 | 90.8 | 0 | 0 | 0 | 100 | 0 | 0 | 0.6 |
| 92 | 0 | 3.2 | 0 | 0 | 1.6 | 2.6 | 0 | 62.2 | 95.6 |
| 92 | 10 | 5.4 | 0 | 0 | 1 | 18.8 | 0 | 19.8 | 89.2 |
| 92 | 25 | 18.4 | 0 | 0 | 0 | 99.6 | 0 | 0 | 60.2 |
| 92 | 50 | 70.2 | 0 | 0 | 0 | 100 | 0 | 0 | 4.4 |

Table 7.5. Summary of the probability of meeting the recovery target and the probability of extinction at year 10 and year 50 for Scenario 4 (declining marine mortality and increasing incidental juvenile mortality) for a population with (Wild + LGB) and without (Wild Only) LGB supplementation.

| | | After 10 Years | | | | After 50 Years | | | |
|---|---|---|---|---|---|---|---|---|---|
| Marine Mortality | Increase in Incidental mortality | Prob. of Extinction | | Prob. of Meeting Recovery Target | | Prob. of Extinction | | Prob. of Meeting Recovery Target | |
| % | % | Wild Only | Wild + LGB | Wild Only | Wild + LGB | Wild Only | Wild + LGB | Wild Only | Wild + LGB |
| 99 | 0 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 2.5 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 5 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 99 | 10 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 |
| 96 | 0 | 43.2 | 0 | 0 | 0 | 100 | 0 | 0 | 38.6 |
| 96 | 2.5 | 49.4 | 0 | 0 | 0 | 100 | 0 | 0 | 31.6 |
| 96 | 5 | 55.2 | 0 | 0 | 0 | 100 | 0 | 0 | 25.6 |
| 96 | 10 | 63.6 | 0 | 0 | 0 | 100 | 0 | 0 | 15.2 |
| 94 | 0 | 9.2 | 0 | 0 | 0.8 | 61.4 | 0 | 4.4 | 81.2 |
| 94 | 2.5 | 11.4 | 0 | 0 | 0.2 | 81.2 | 0 | 1.2 | 76.6 |
| 94 | 5 | 14.4 | 0 | 0 | 0 | 94.2 | 0 | 0 | 71.6 |
| 94 | 10 | 20 | 0 | 0 | 0 | 99.6 | 0 | 0 | 54.8 |
| 92 | 0 | 3.2 | 0 | 0 | 1.6 | 2.6 | 0 | 62.2 | 95.6 |
| 92 | 2.5 | 3.6 | 0 | 0 | 1.2 | 5 | 0 | 48.8 | 94.4 |
| 92 | 5 | 3.8 | 0 | 0 | 1.2 | 8.4 | 0 | 33.6 | 91.8 |
| 92 | 10 | 5 | 0 | 0 | 0.6 | 30 | 0 | 12.2 | 85.6 |

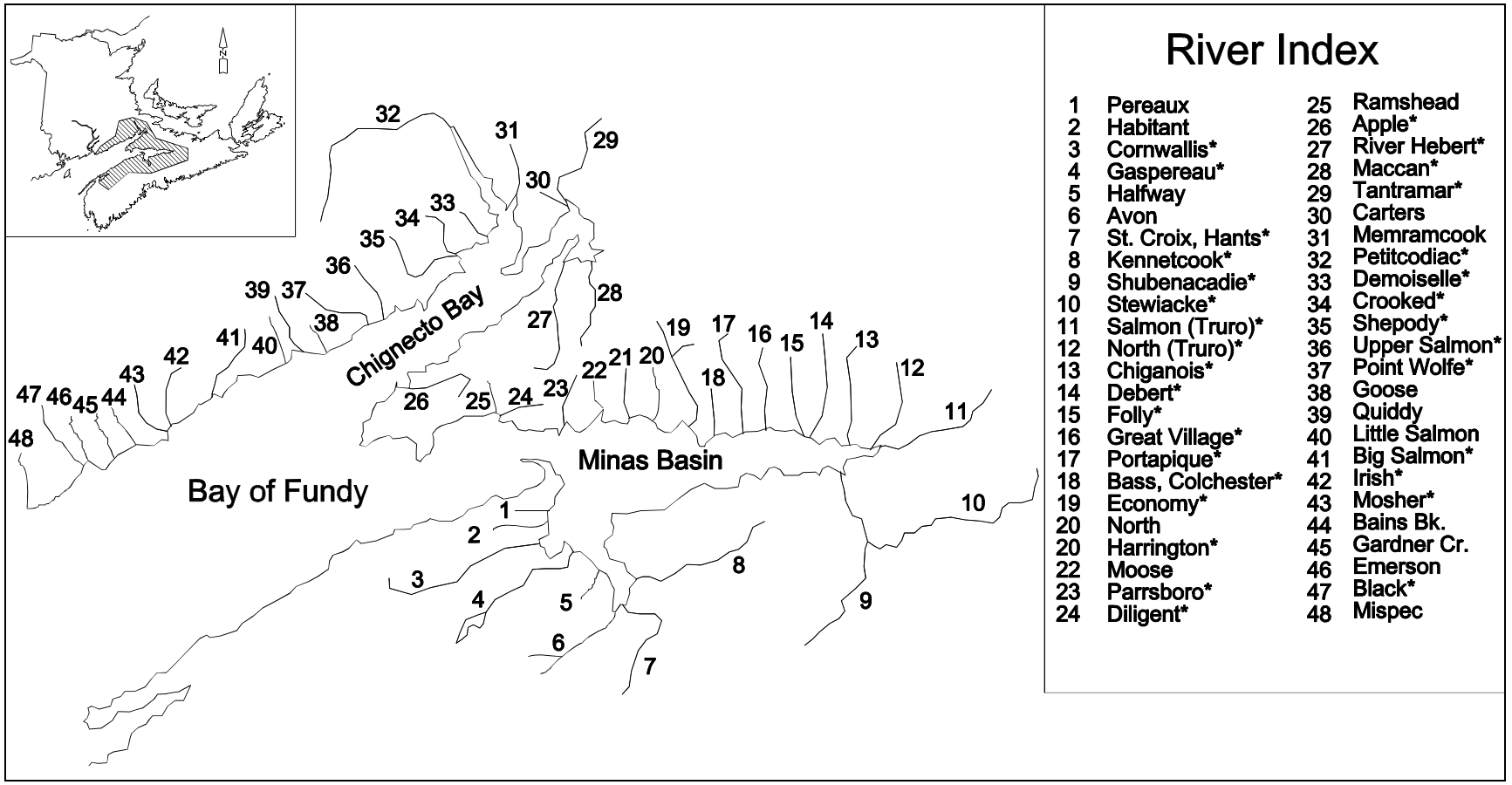


Figure 2.1. Map showing the approximate locations of inner Bay of Fundy rivers referred to in this report. Rivers in which a reported recreational catch, or electrofishing surveys have confirmed the past presence of Atlantic salmon are marked with an asterisks (adapted from Amiro 2003).

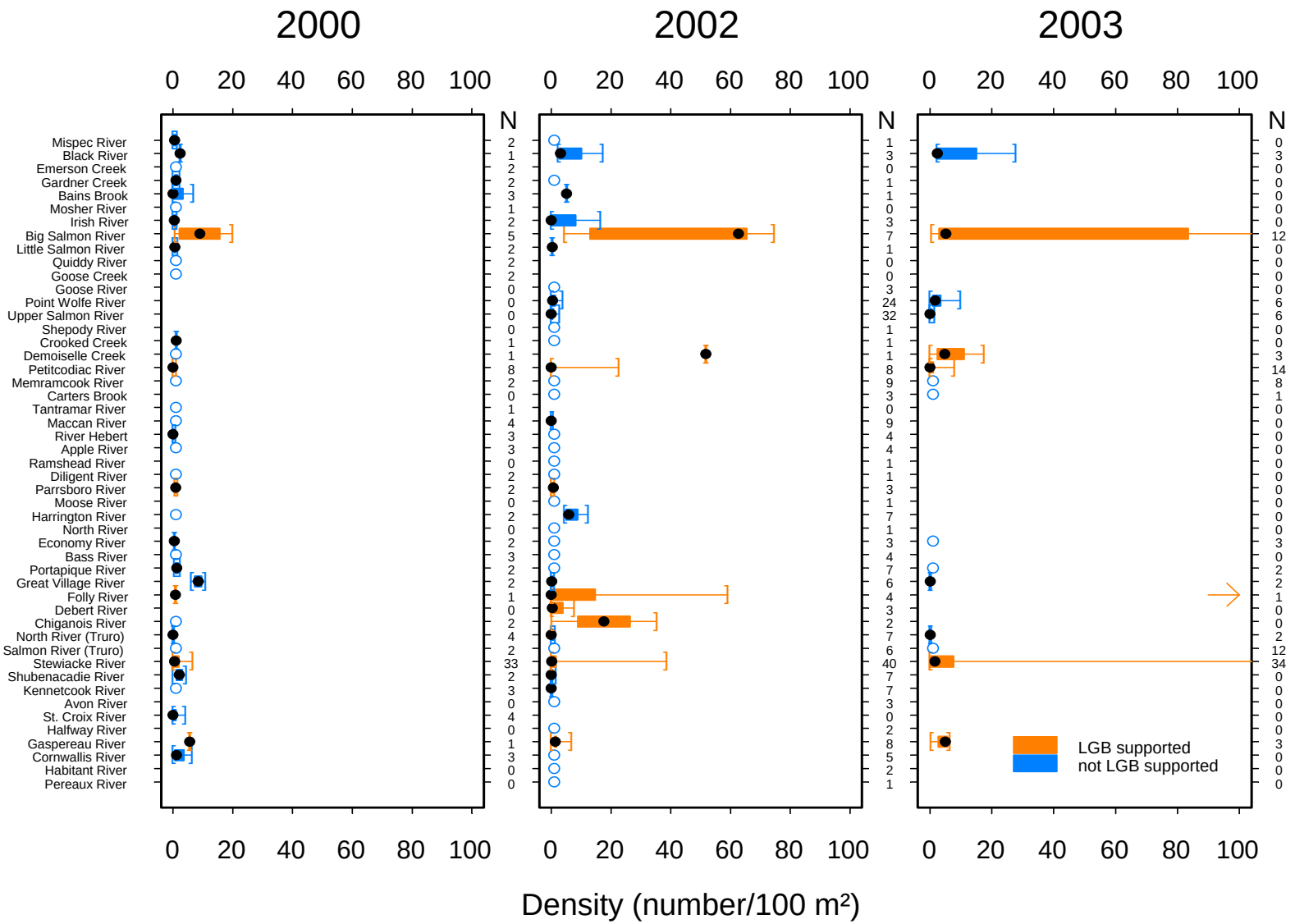


Figure 2.2. Box plots showing the density of Atlantic salmon in inner Bay of Fundy rivers based on electrofishing during 2000, 2002, and 2003. The dot shows the median density and the box shows the inter-quartile spread. The whiskers are drawn to the minimum and maximum. LGB (Live Gene Bank) supported rivers are where juvenile Atlantic salmon had been released since 1996 and prior to electrofishing. Densities outside the range of the graph are marked with an arrow. O's mark rivers in which salmon were not captured. Rivers with blank spaces were not electrofished in those years (from Gibson et al. 2004).

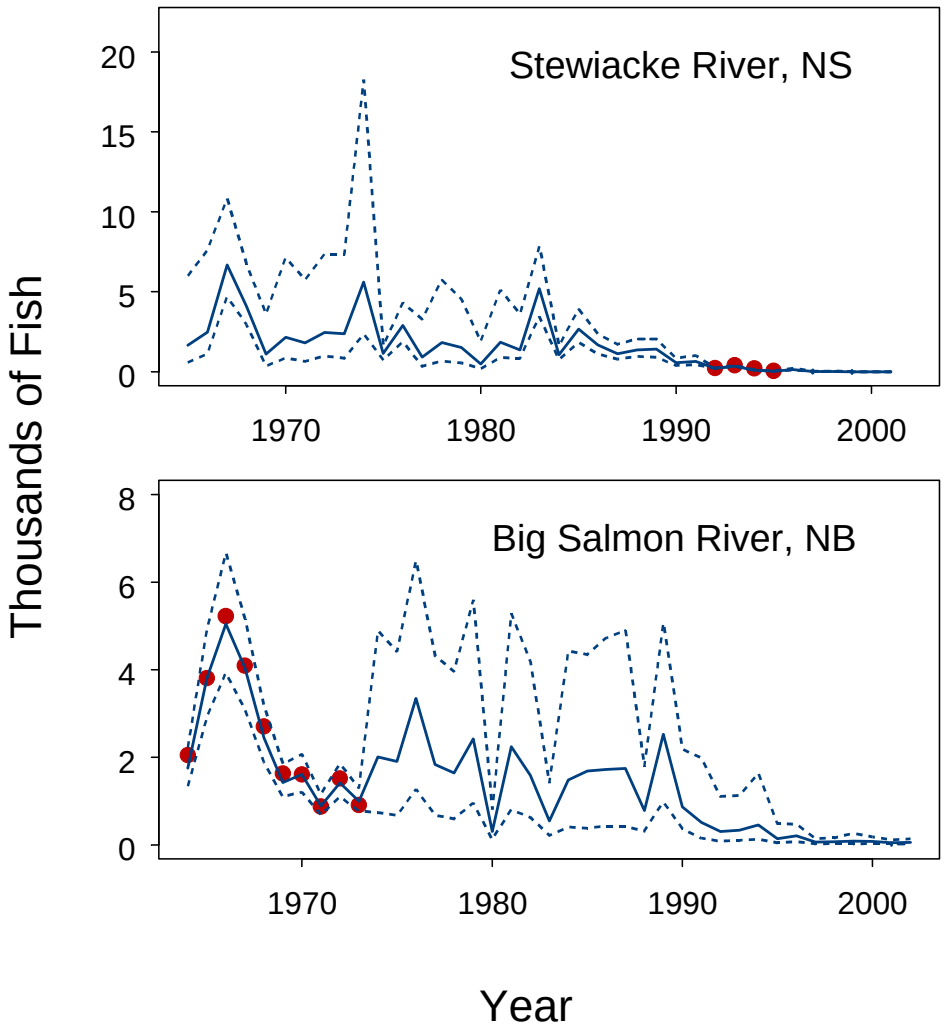


Figure 3.1. Trends in abundance in the 2 iBoF salmon index populations (adapted from Gibson and Amiro 2003, and Gibson et al. 2003b).

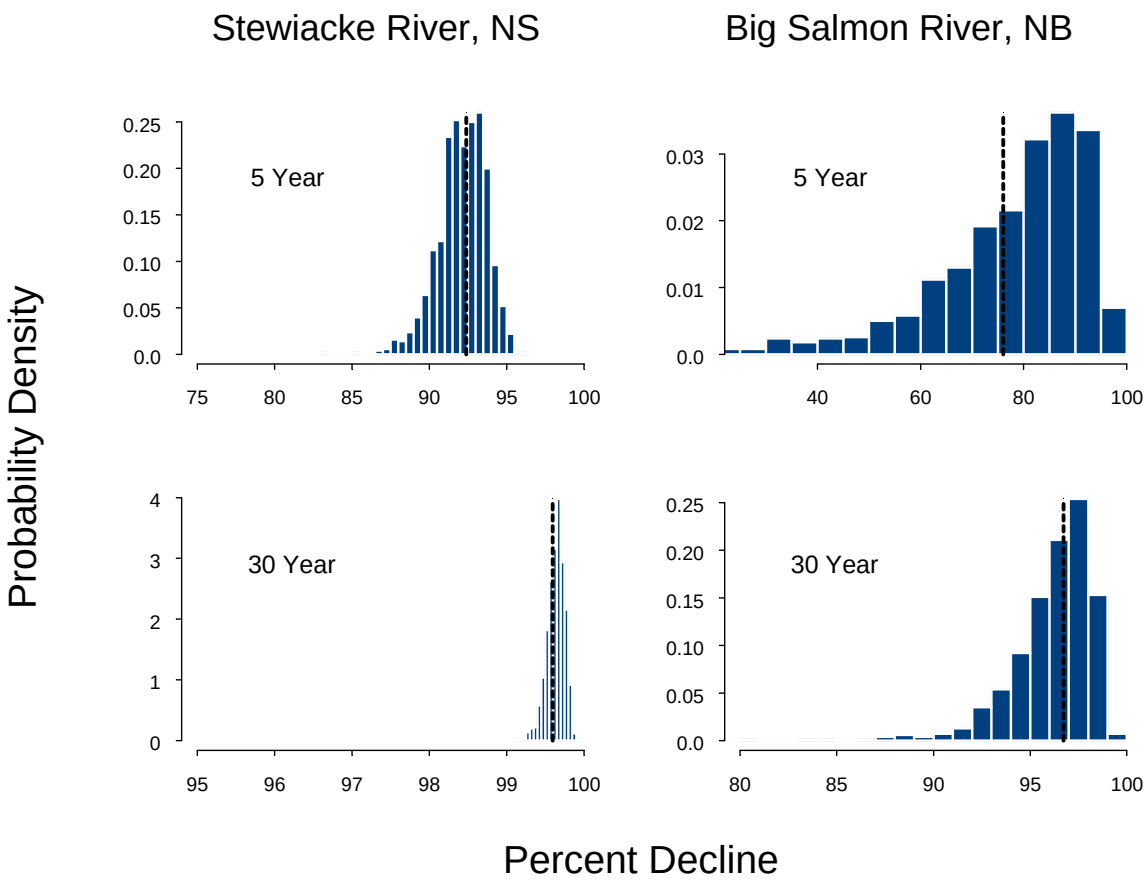


Figure 3.2. Posterior probability densities for the percent decline in 5-year mean population size over 2 time periods for the 2 iBoF salmon index populations (adapted from Gibson and Amiro 2003, and Gibson et al. 2003b). The dashed vertical line shows the median of the distribution.

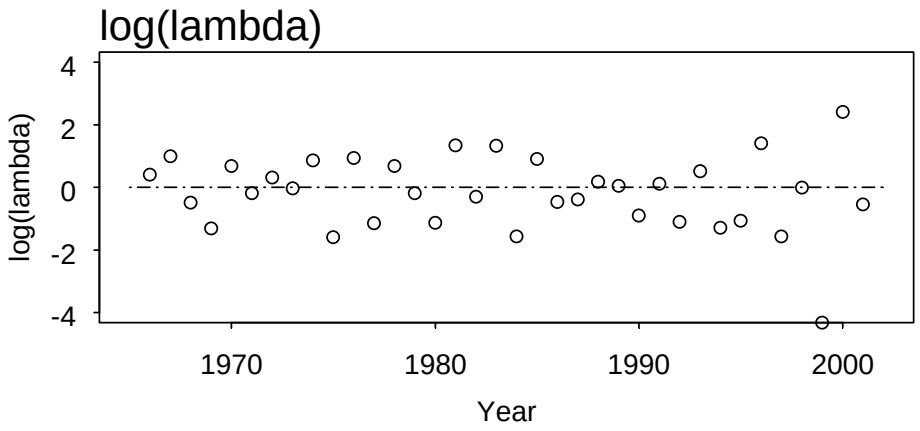


Figure 5.1. Trend in the log of $\lambda$ ($N_{t+1} / N_t$) for the Stewiacke River population from 1965 to 2002.

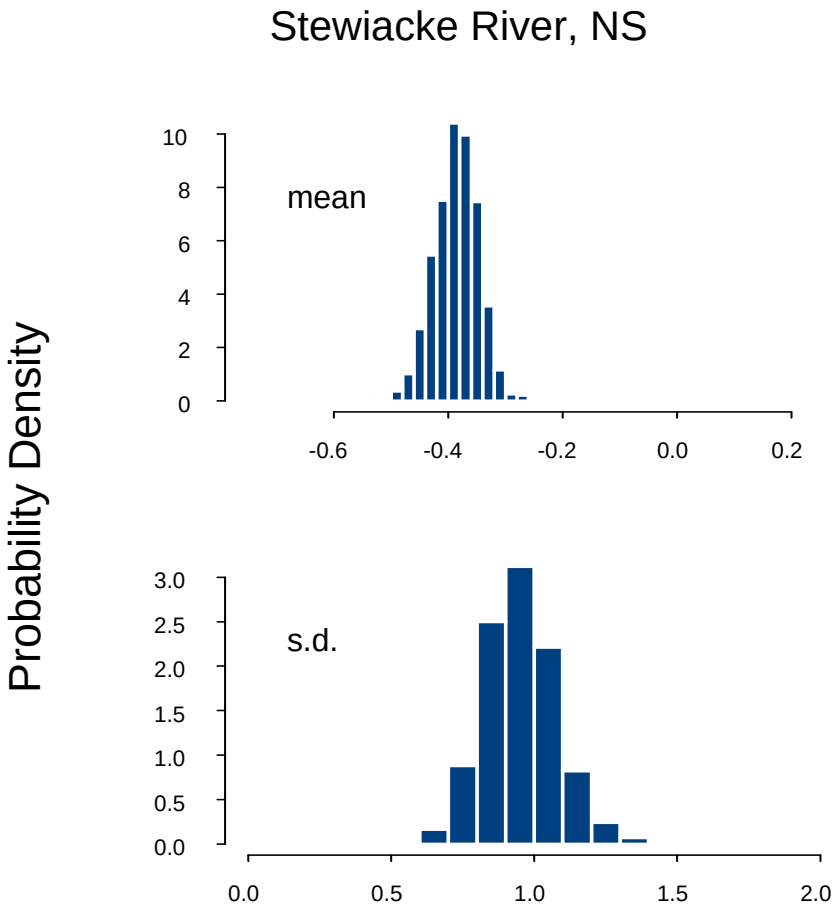


Figure 5.2. Posterior probabilities for mean (top) and standard deviation (bottom) of the log of the rate of change in the number of adult salmon (lambda) for the Stewiacke River.

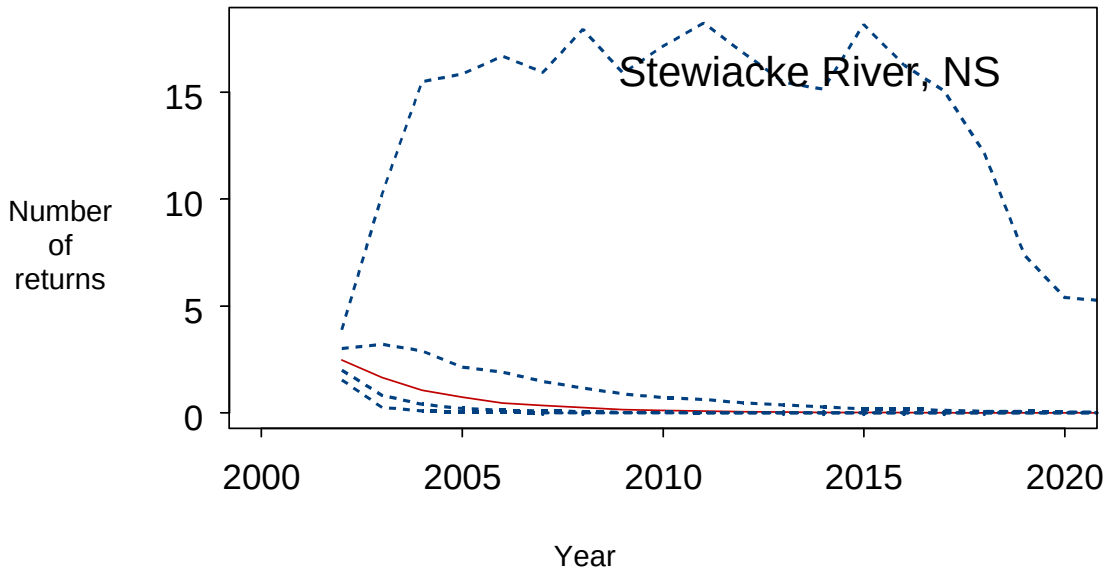


Figure 5.3. Summary of the predicted population size for the Stewiacke River, N.S., salmon population using a Bayesian version of the Dennis model. The solid line is the median population size and dashed lines are the 10$^{th}$, 30$^{th}$, 70$^{th}$, and 90$^{th}$ percentiles of the posterior distributions for the projected annual population size.

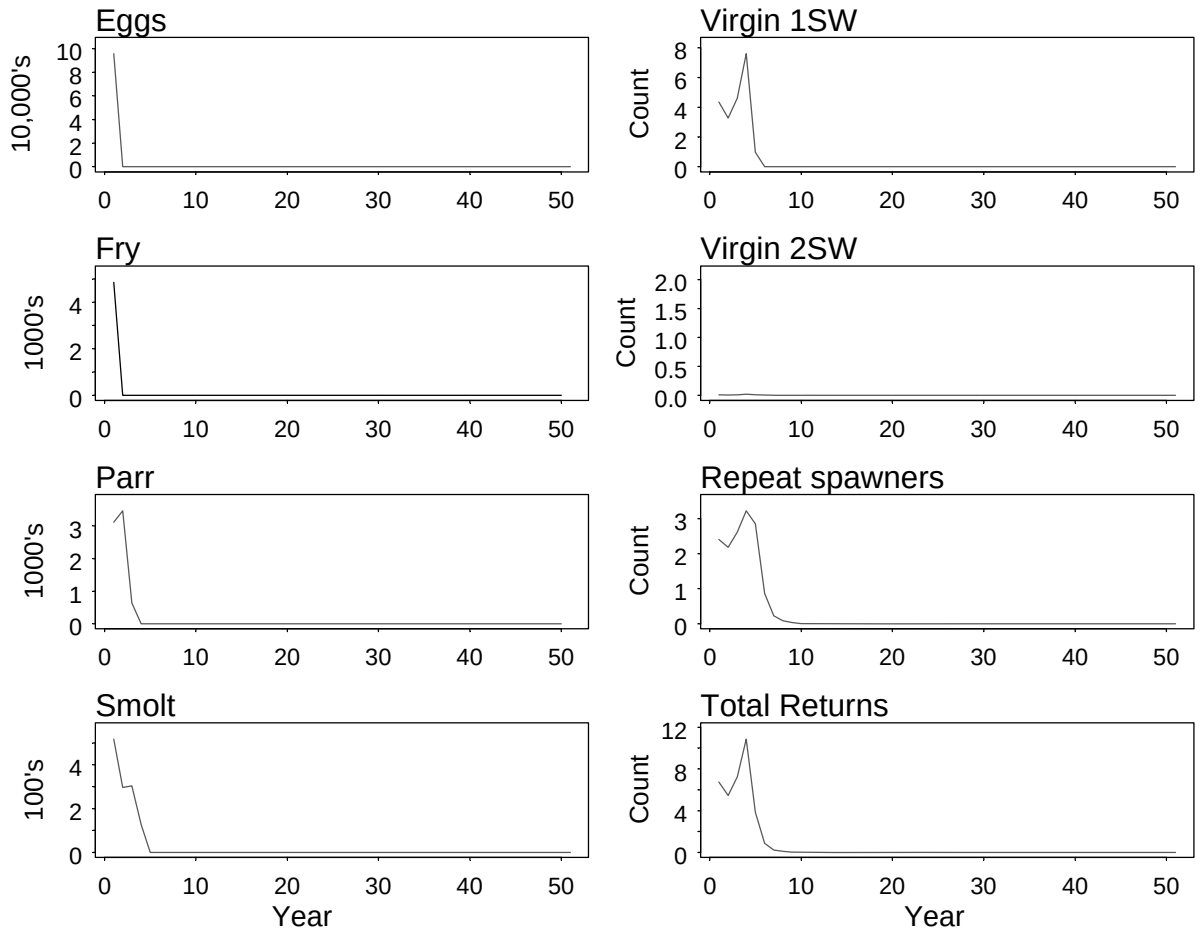


Figure 5.4. Predicted median abundance of each life stage of Big Salmon River salmon for the next 50 years, based on a single PVA model run in the absence of a LGB program.

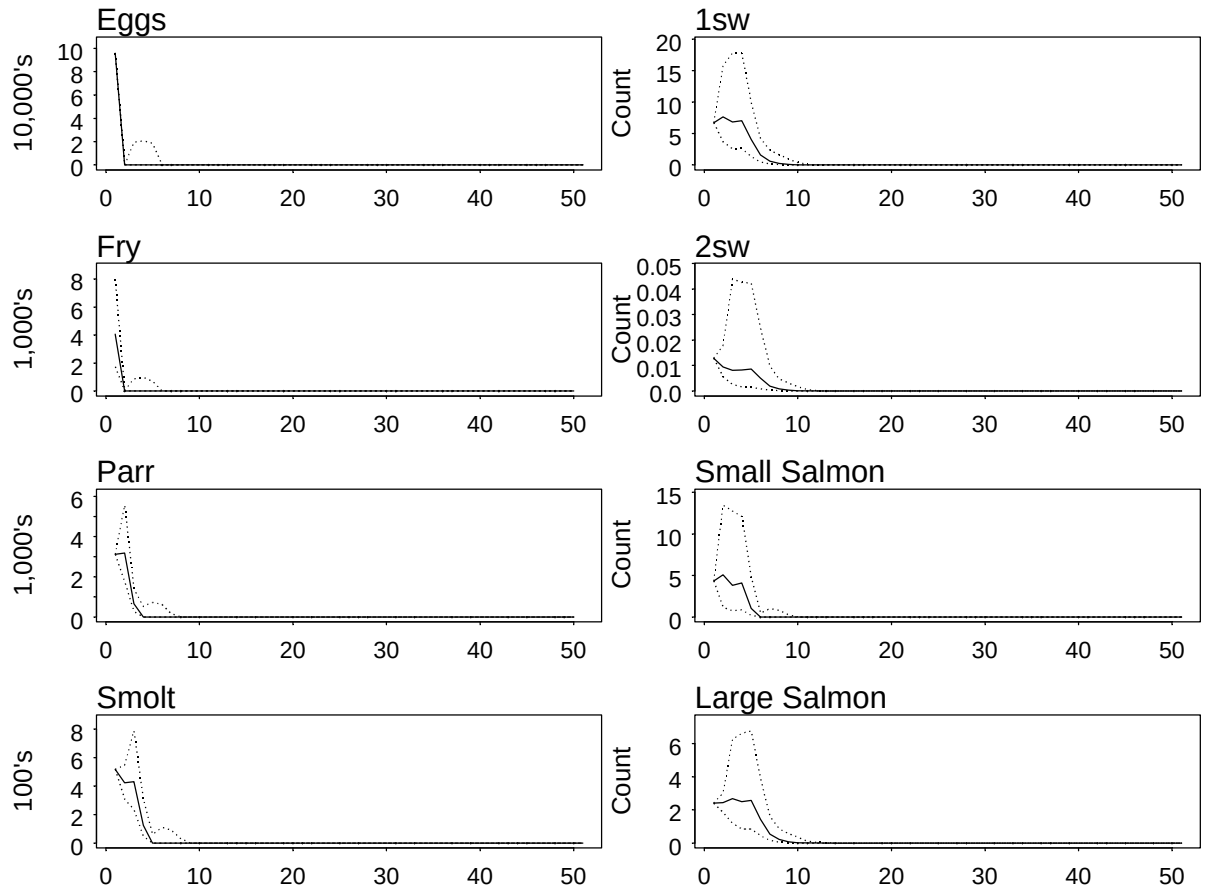


Figure 5.5. Predicted median abundance (solid line) with the 10th and 90th percentiles (dashed lines) from 400 iterations of the PVA projection model for each life stage of an Atlantic salmon population without LGB support. In the absence of human intervention, all life stages are predicted to go extinct within 10 years.

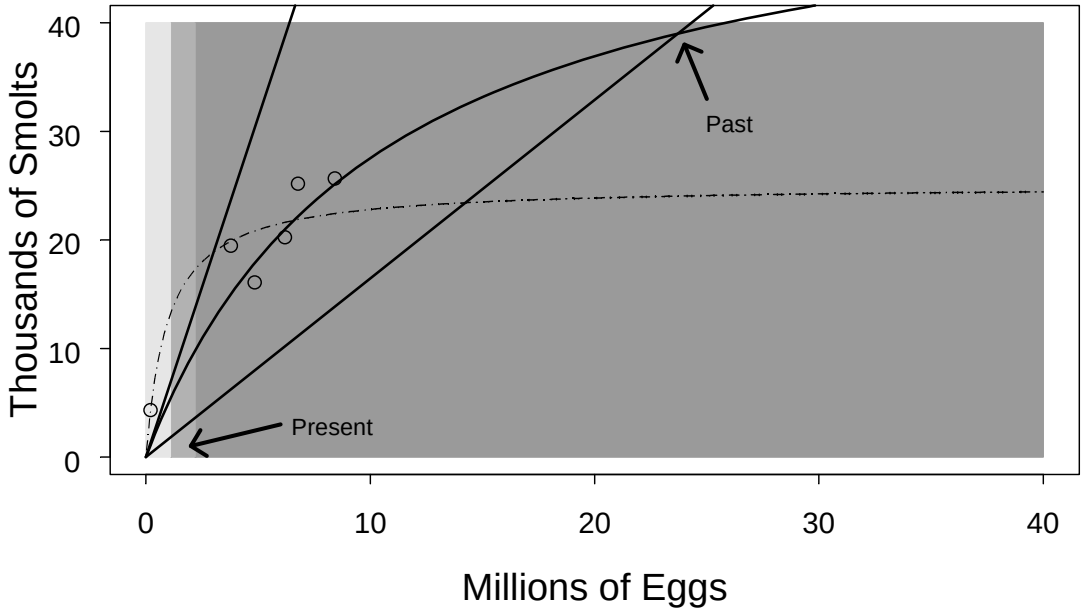


Figure 6.1. Equilibrium analysis for salmon of the Big Salmon River, N.B., showing the change equilibrium population size resulting from a decrease in at-sea survival between 2 time periods, the past (1967-1971) and present (2001-2004). The solid curved line shows the freshwater production curve that results when a life history model is fit to all available data. The dashed curved line shows a Beverton-Holt function fit to the 6 data points for the egg deposition years 1966-1971 and 2001. The 2 straight lines are the replacement lines calculated using the past and present dynamics estimated using the life history model. Shading indicates the status relative to the conservation egg requirement: dark shading is above the requirement, the medium shading is between 50% and 100% the egg requirement and the light shading is below the requirement.

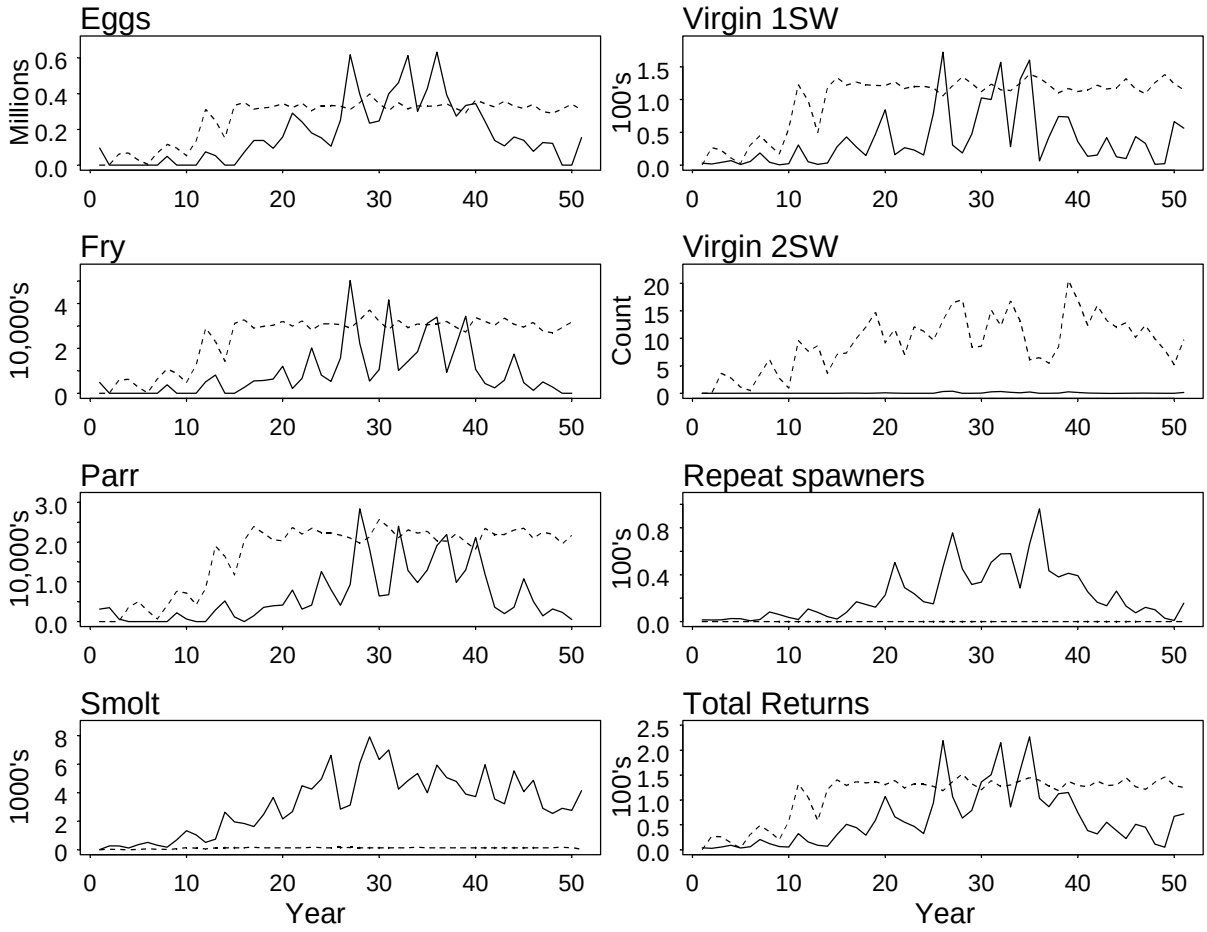


Figure 7.1. Example of a single population projection over a 50 year time period for all life stages of an Atlantic salmon population with LGB support. Predicted total median abundance is split into the wild component (solid lines) and the LGB component (dashed lines) of the population for comparison.

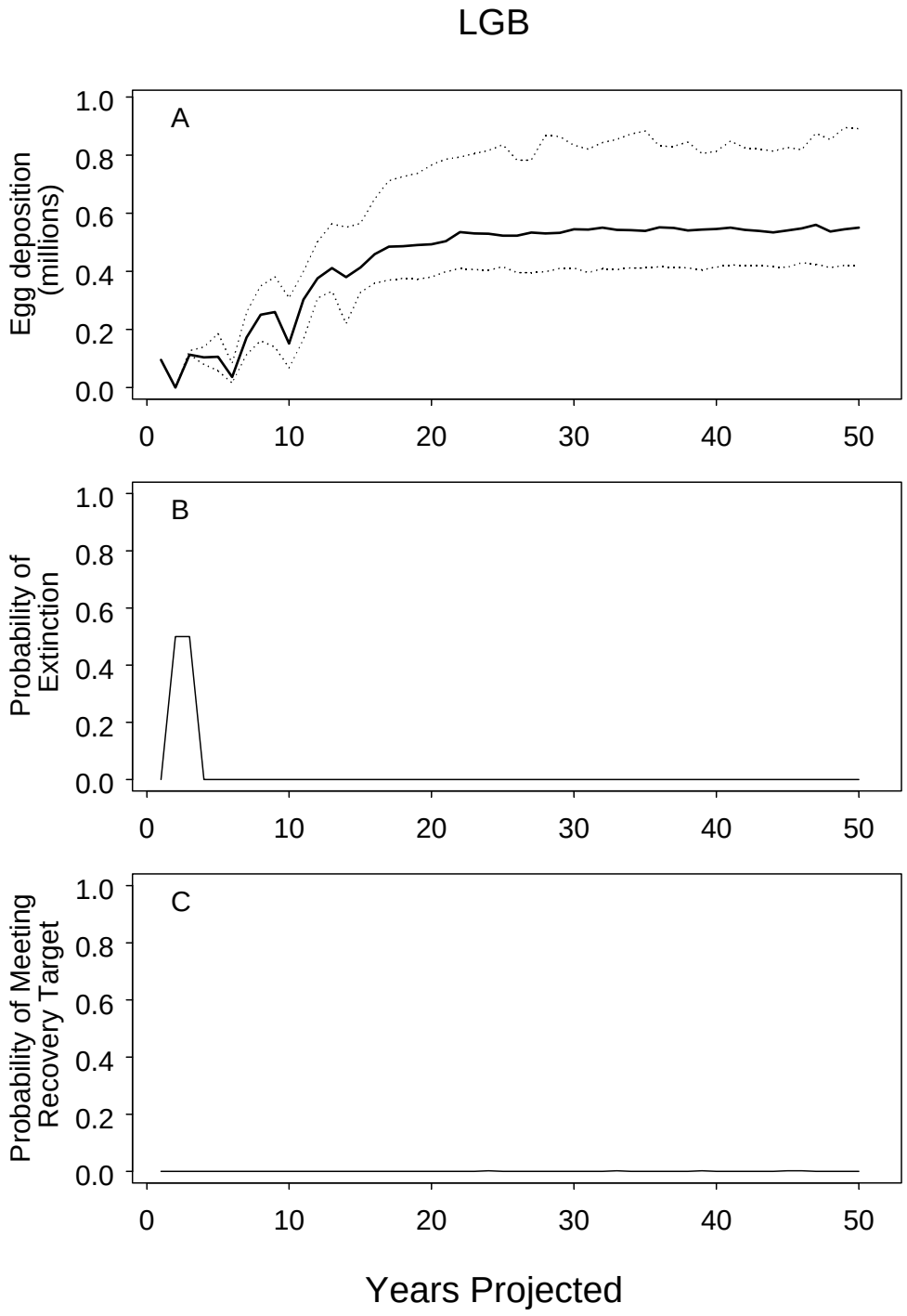


Figure 7.2. Predicted median egg deposition for the next 50 years, shown with the 10th and 90th percentiles (top panel), for an Atlantic salmon population with LGB support. The corresponding probability of extinction (middle panel) and the probability of meeting the recovery target (bottom panel) over the same timeframe are given.

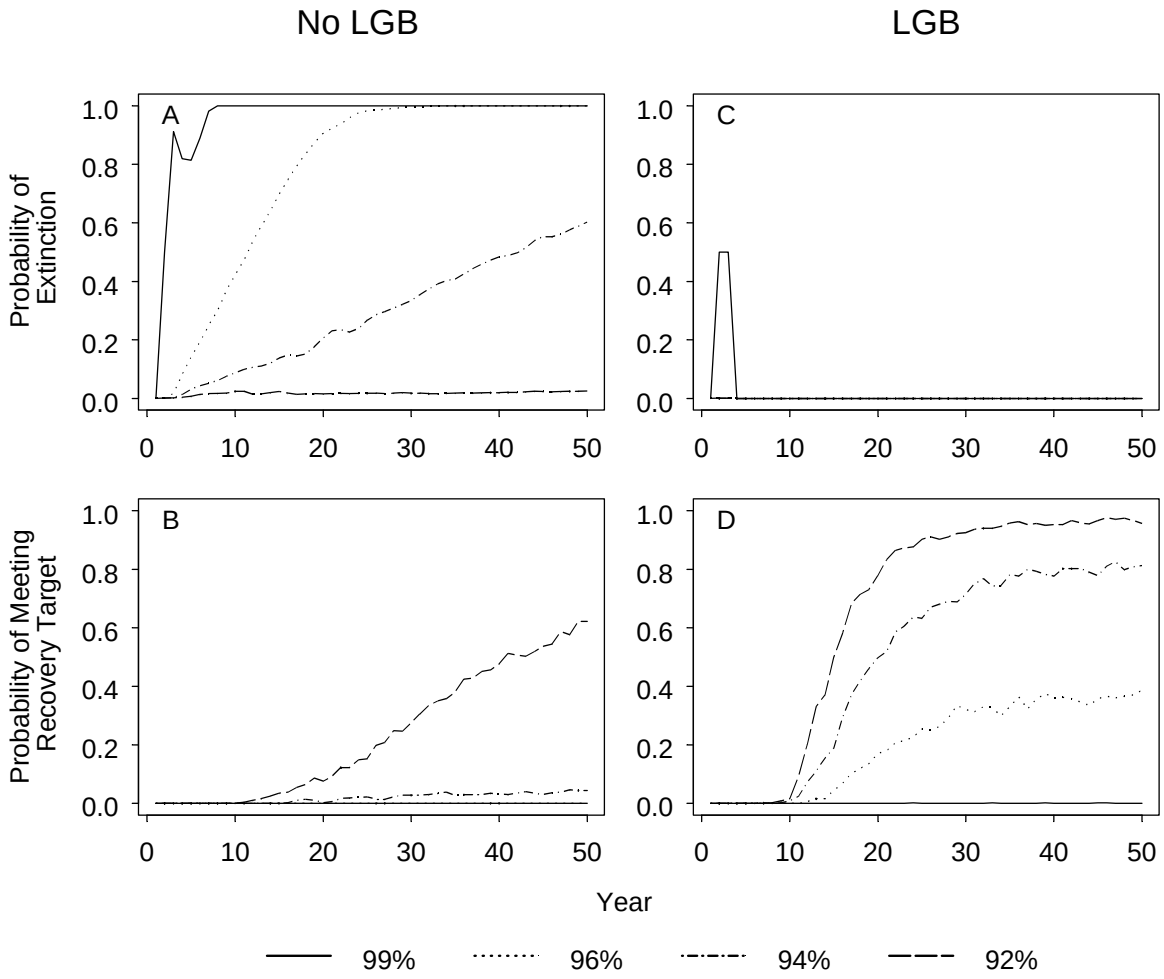


Figure 7.3. The probability of extinction for a population with (panel A) and without (panel C) LGB support when at-sea mortality rates range from 99% (recent estimate) to 92% (historical estimate) while all other life history parameters are held constant at present rates. The corresponding probability of meeting the recovery target as at-sea mortality declines is given for a population with (panel B) and without (panel D) LGB support.

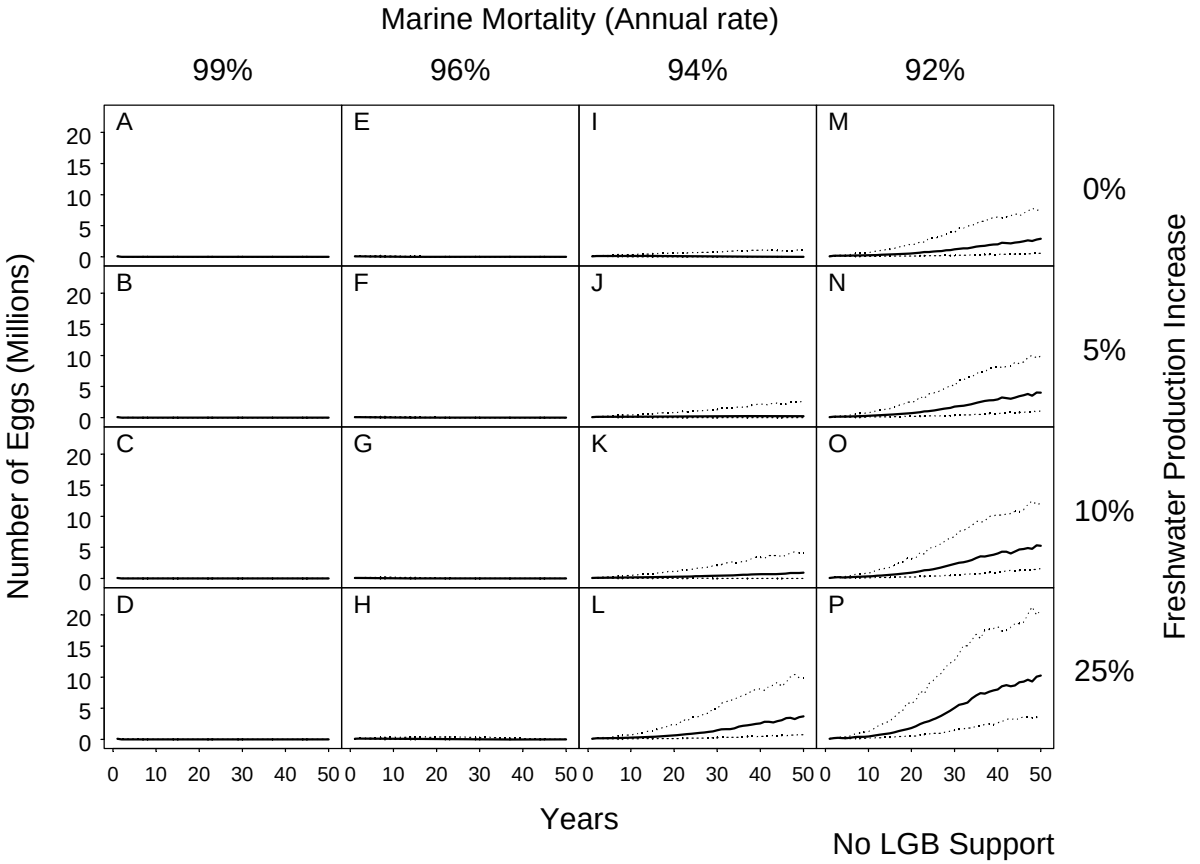


Figure 7.4. Predicted median egg abundance (solid line) and the 10th and 90th percentiles (dotted lines) under Scenario 1 (decreasing at-sea mortality and increasing freshwater productivity) for an Atlantic salmon population without LGB support.

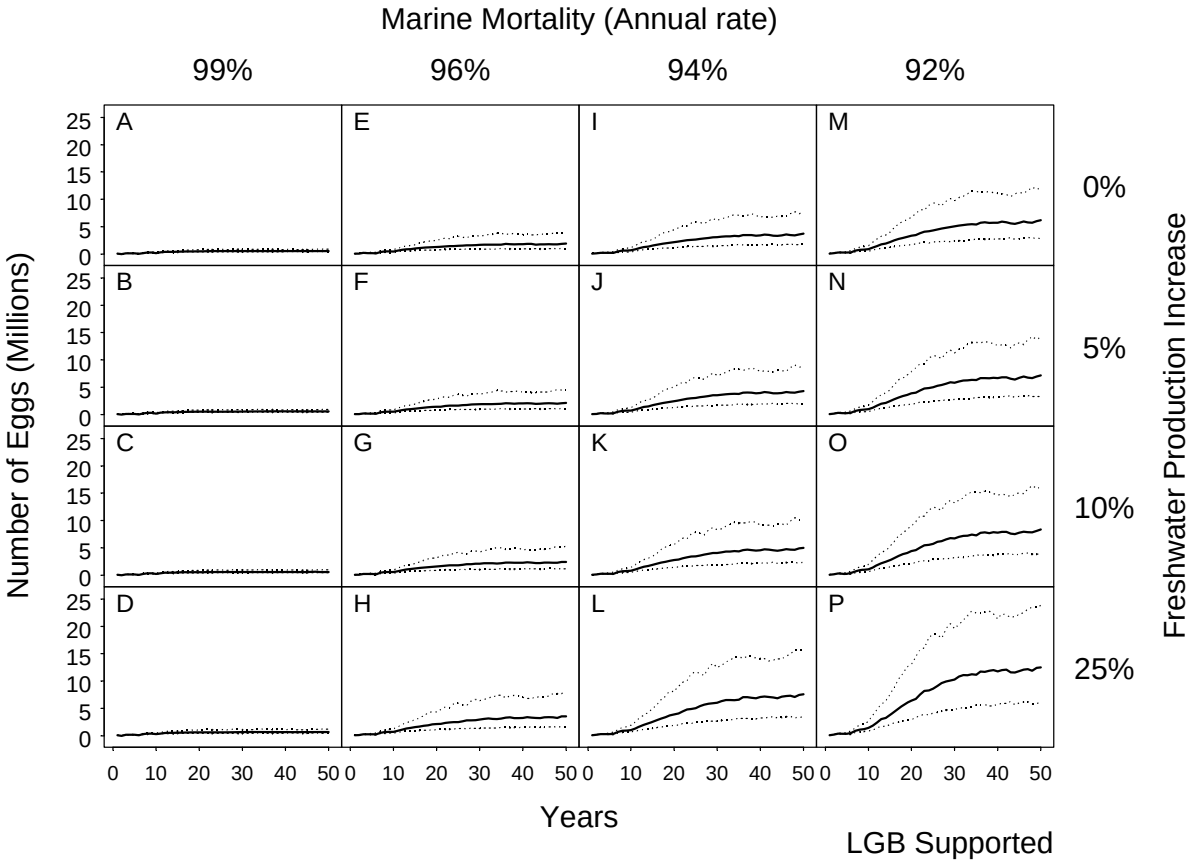


Figure 7.5. Predicted median egg abundance (solid line) and the 10th and 90th percentiles (dotted lines) under Scenario 1 (decreasing at-sea mortality and increasing freshwater productivity) for an Atlantic salmon population with LGB support.

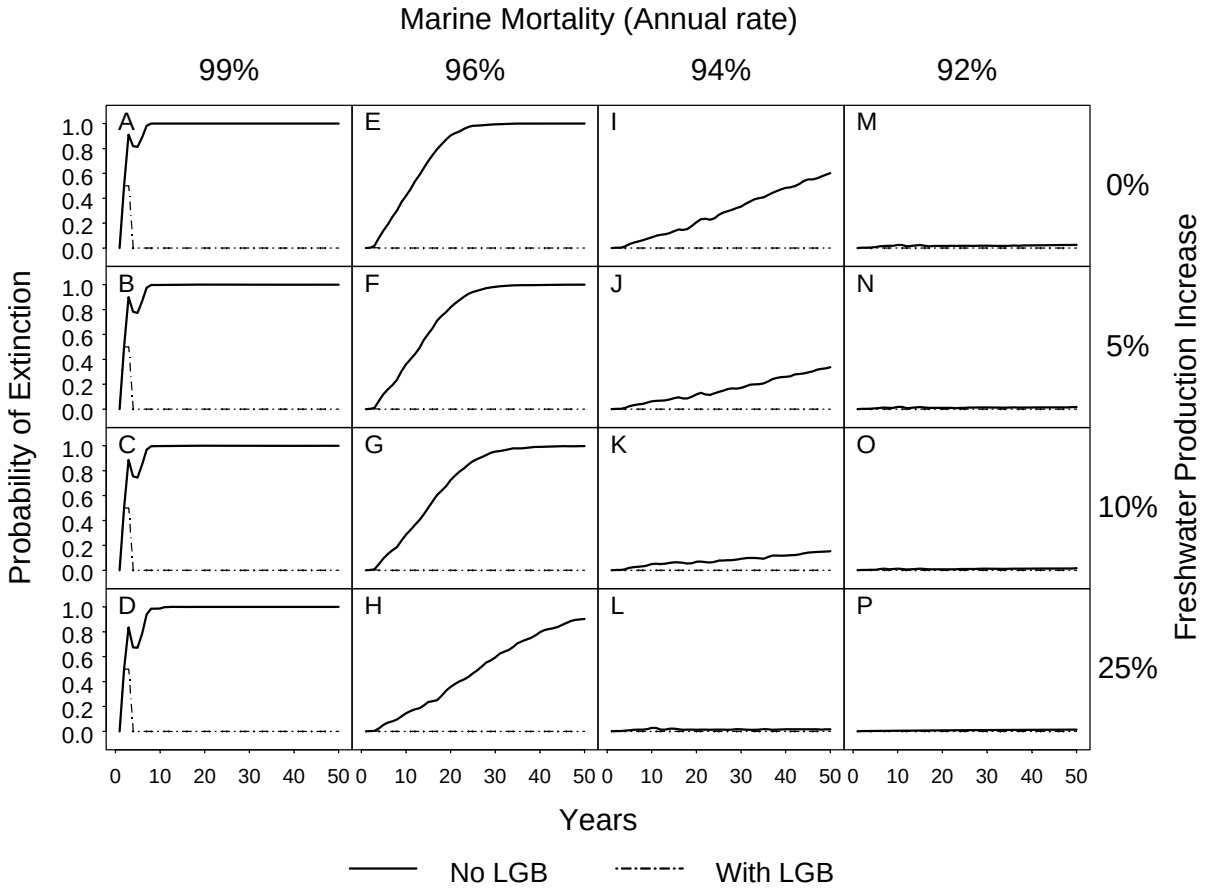


Figure 7.6. The probability of extinction under Scenario 1 (declining marine mortality and increasing freshwater productivity) for an Atlantic salmon population with and without LGB support.

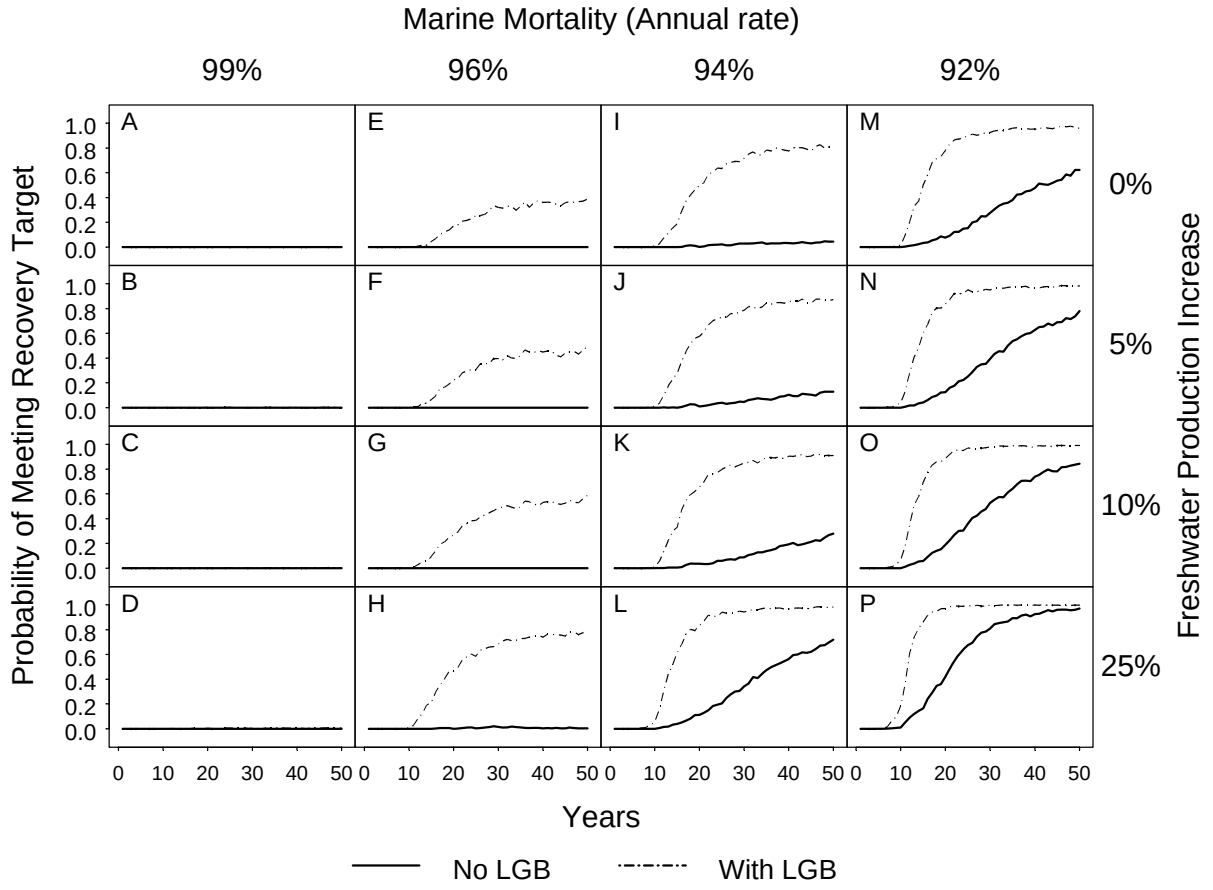


Figure 7.7. The probability of meeting the recovery target under Scenario 1 (declining marine mortality and increasing freshwater productivity) for an Atlantic salmon population with and without LGB support.

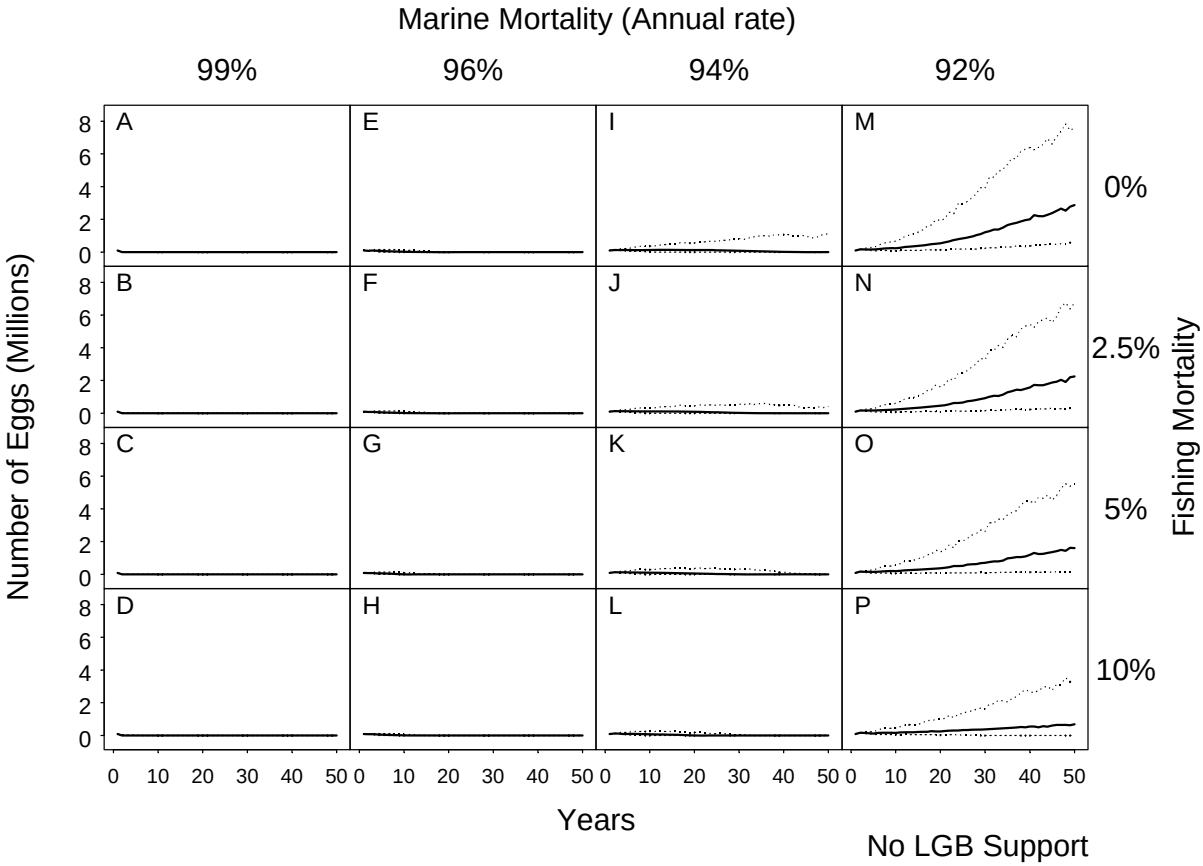


Figure 7.8. Predicted median egg abundance (solid line) and 10th and 90th percentiles (dotted lines) under Scenario 2 (decreasing at-sea mortality and additional fishing mortality) for an Atlantic salmon population without LGB support.

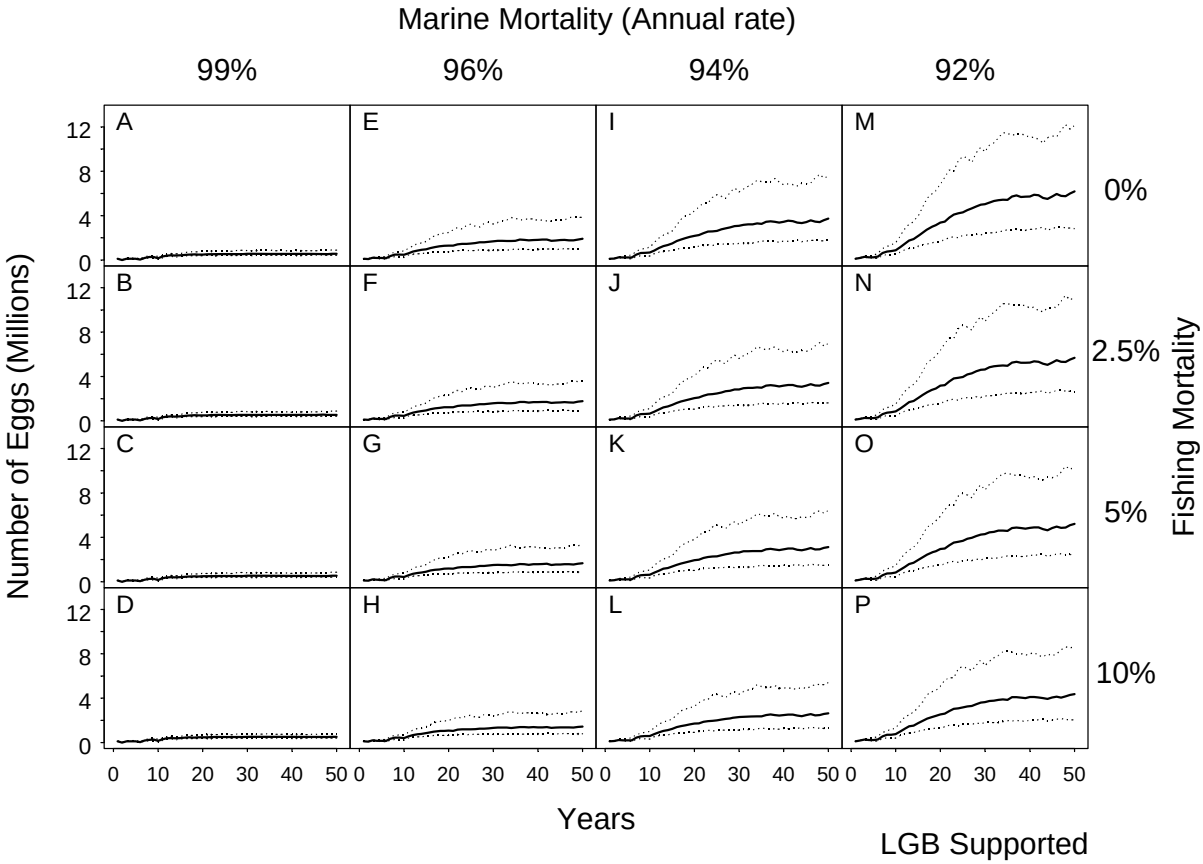


Figure 7.9. Predicted median egg abundance (solid line) and 10$^{th}$ and 90$^{th}$ percentiles (dotted lines) under Scenario 2 (decreasing at-sea mortality and additional fishing mortality) for an Atlantic salmon population with LGB support.

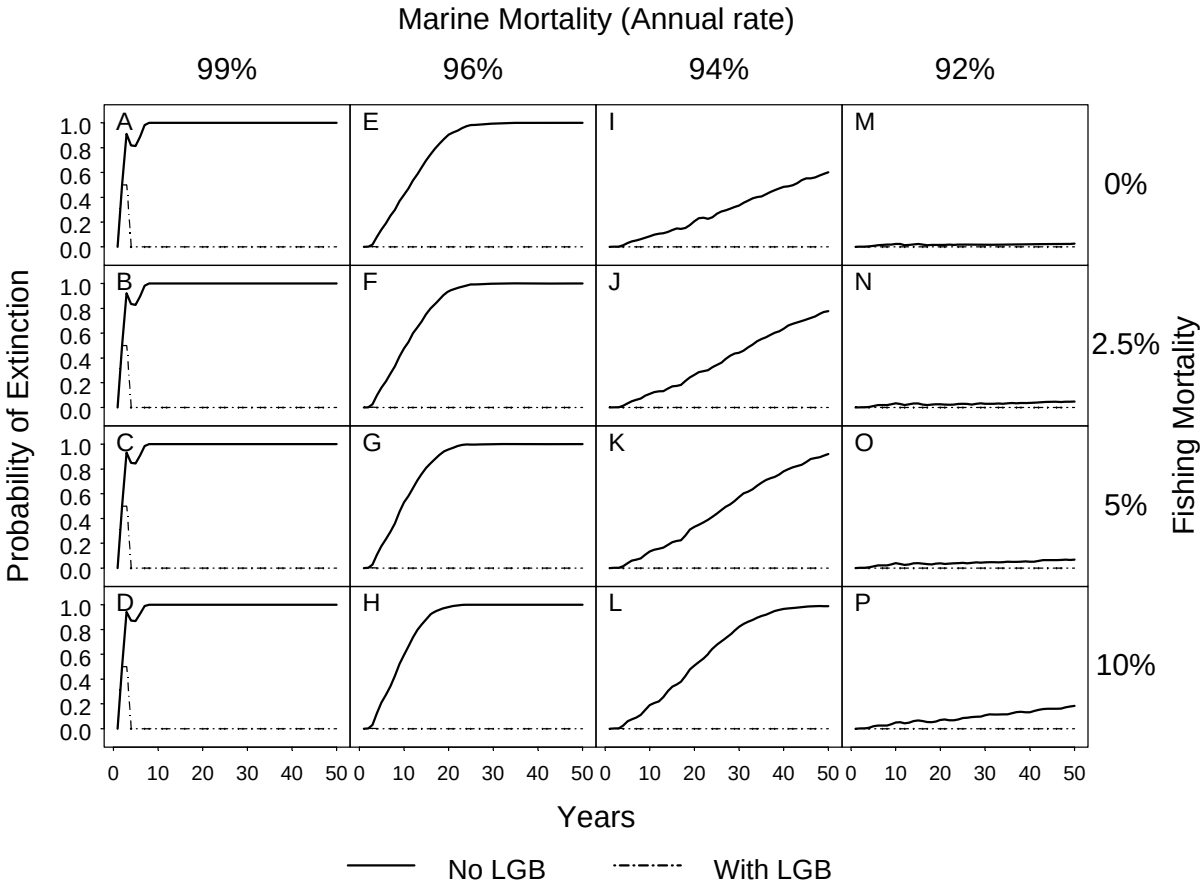


Figure 7.10. The probability of extinction under Scenario 2 (decreasing at-sea mortality and additional fishing mortality) for an Atlantic salmon population with and without LGB support.

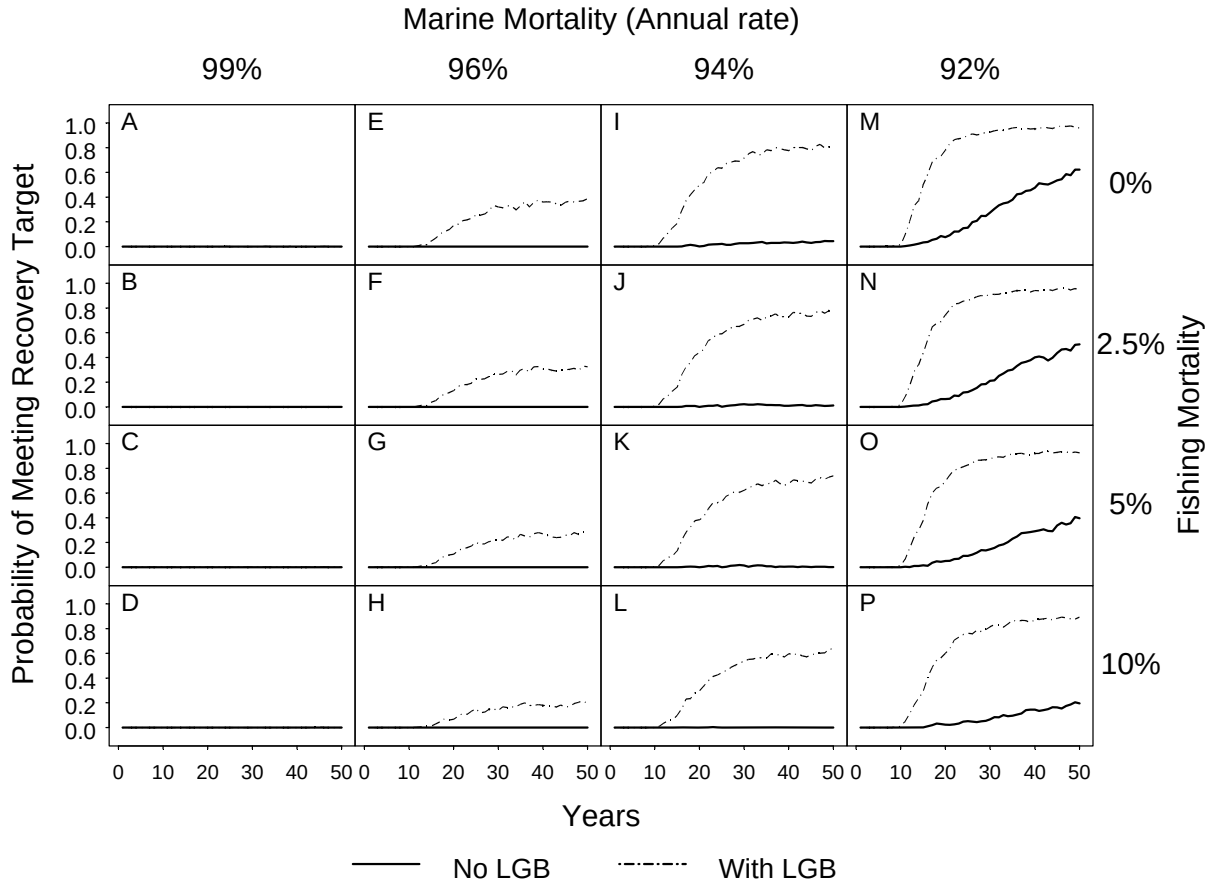


Figure 7.11. The probability of meeting the recovery target under Scenario 2 (decreasing at-sea mortality and additional fishing mortality) for an Atlantic salmon population with and without LGB support.

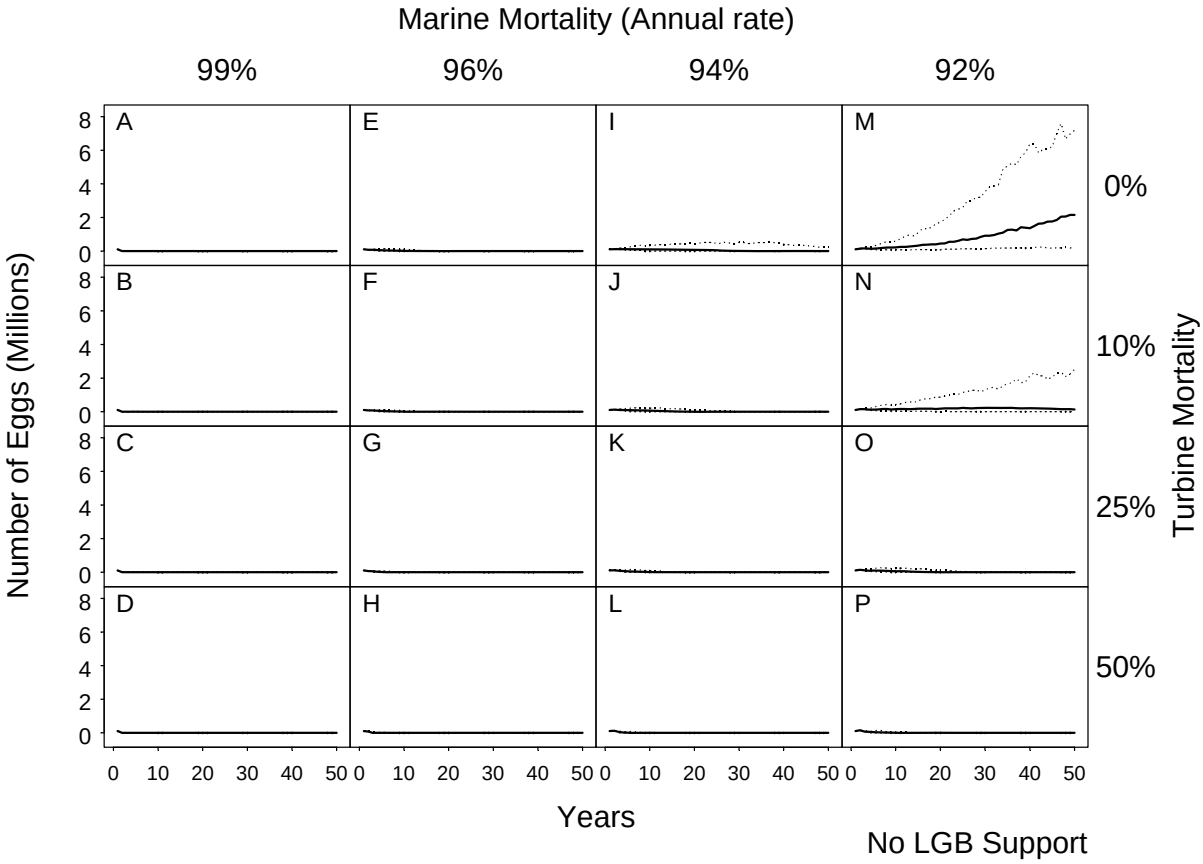


Figure 7.12. Predicted median (solid line) and 10th and 90th percentiles (dotted lines) egg deposition under Scenario 3 (declining at-sea mortality and increasing turbine mortality on downstream migrating smolts and post-spawners) in an Atlantic salmon population without LGB support.

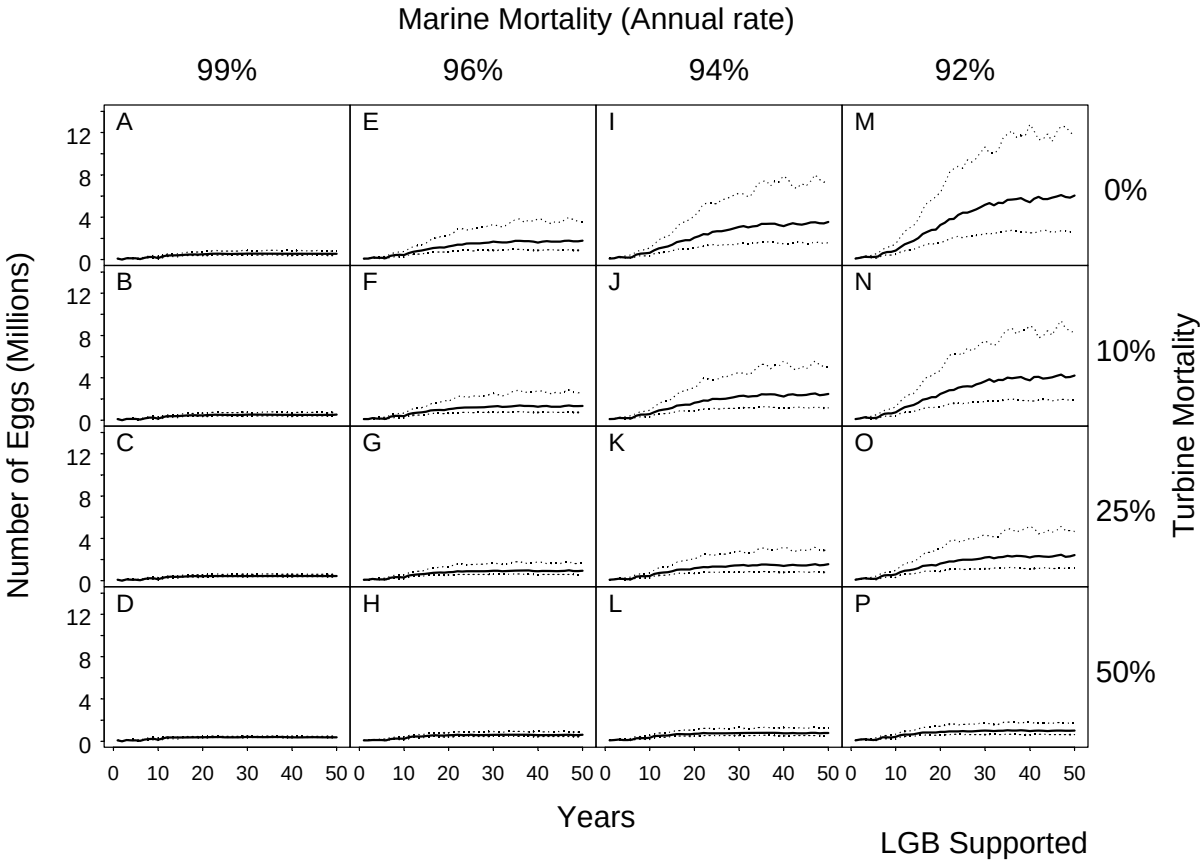


Figure 7.13. Predicted median (solid line) and 10$^{th}$ and 90$^{th}$ percentile (dotted lines) egg deposition under Scenario 3 (declining at-sea mortality and increasing turbine mortality on downstream migrating smolts and post-spawners) in an Atlantic salmon population with LGB support.

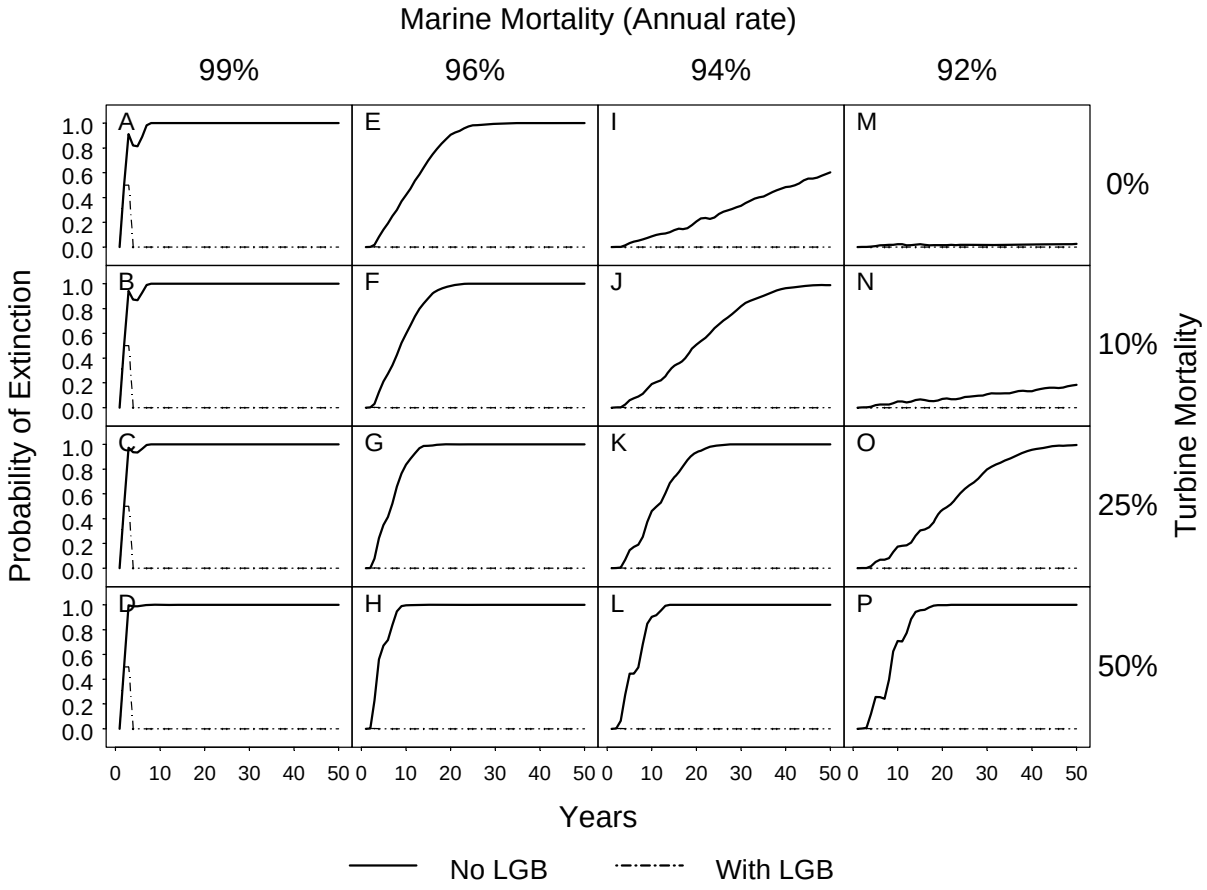


Figure 7.14. The probability of extinction under Scenario 3 (declining at-sea mortality and increasing turbine mortality) for an Atlantic salmon population with and without LGB support.

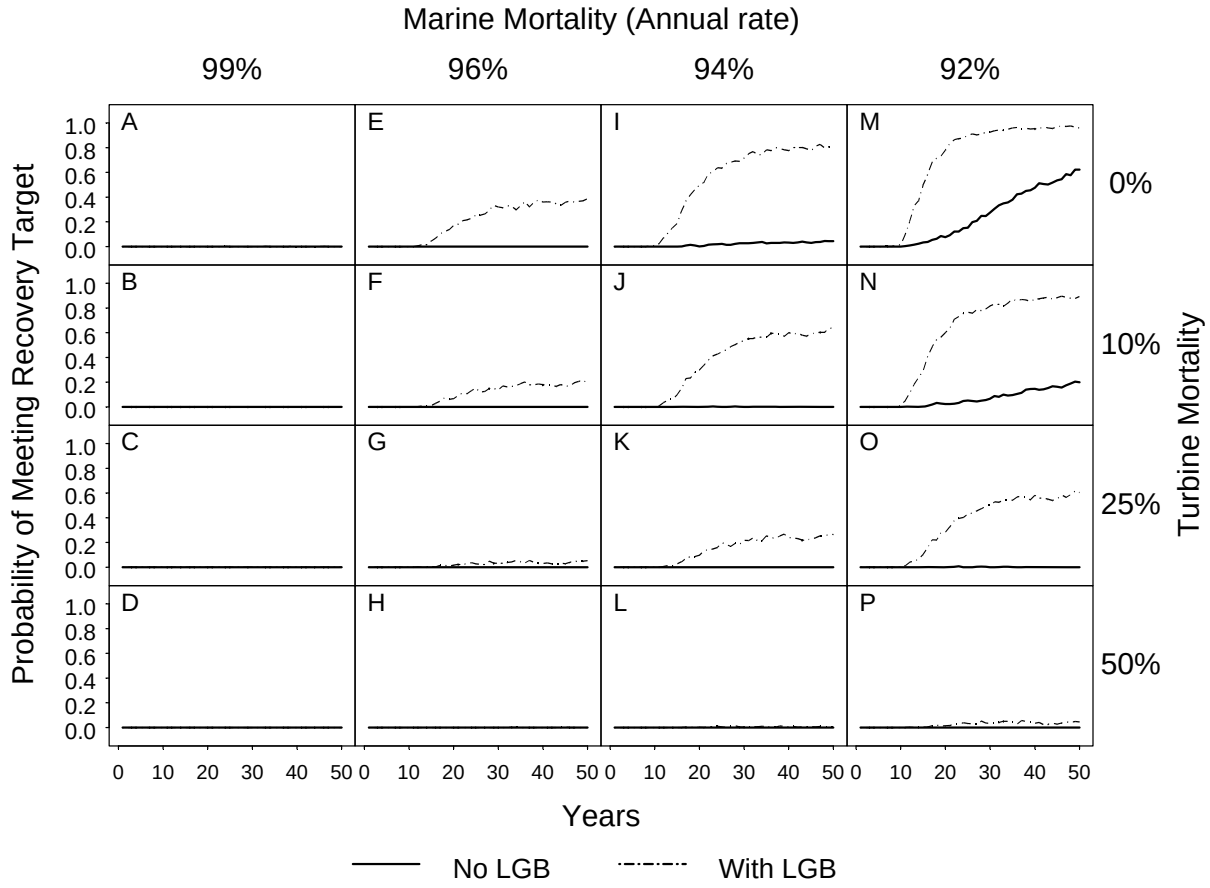


Figure 7.15. The probability of meeting the recovery target under Scenario 3 (declining at-sea mortality and increasing turbine mortality) for an Atlantic salmon population with and without LGB support.

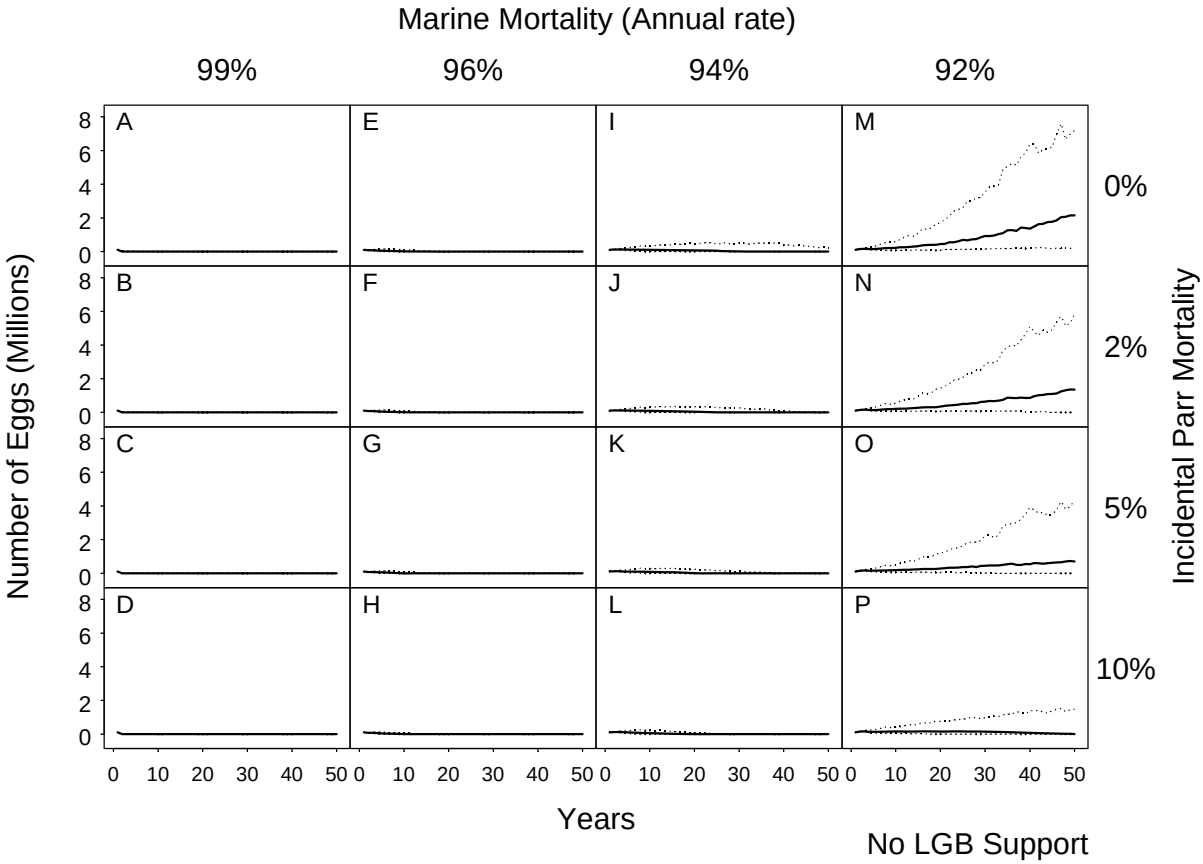


Figure 7.16. Predicted median (solid line) and 10$^{th}$ and 90$^{th}$ percentile (dotted lines) egg depositions under Scenario 4 (declining at-sea mortality and increasing incidental parr mortality) for an Atlantic salmon population without LGB support.

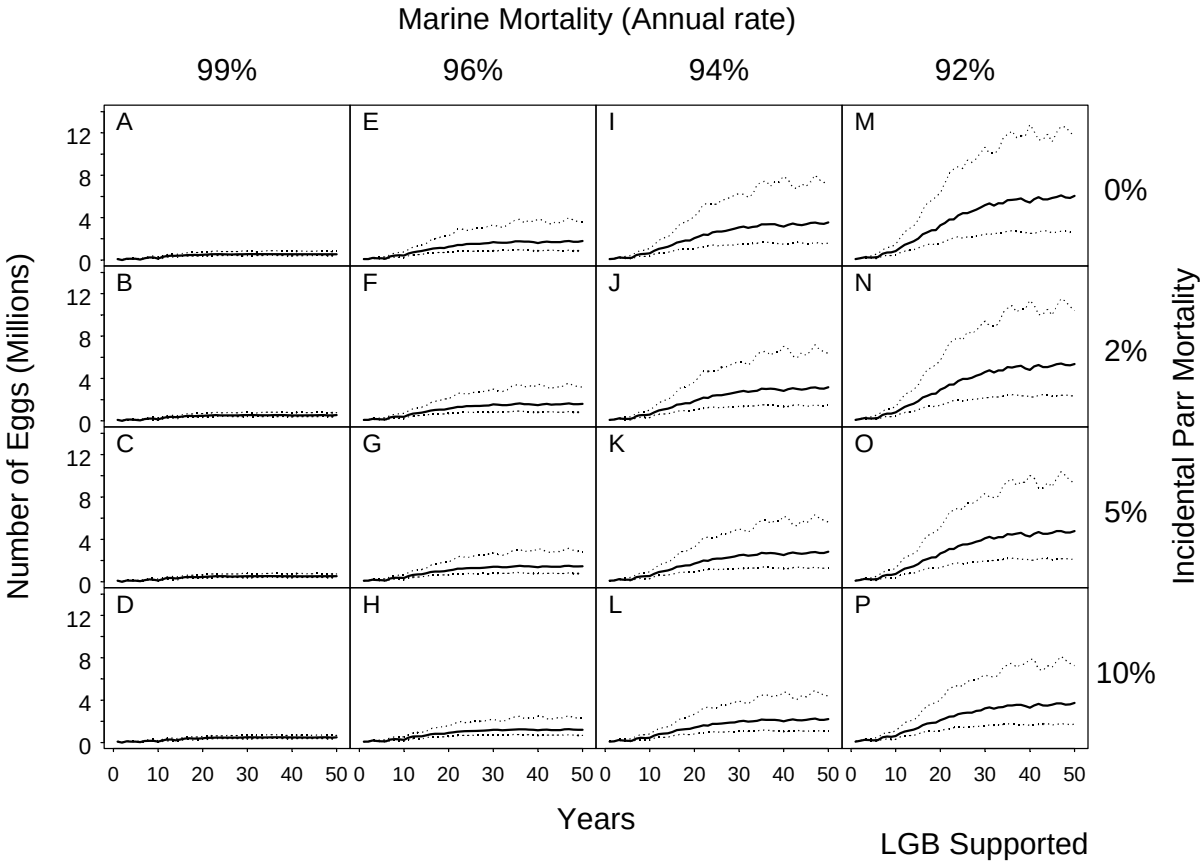


Figure 7.17. Predicted median (solid line) and 10$^{th}$ and 90$^{th}$ percentile (dotted lines) egg depositions under Scenario 4 (declining at-sea mortality and increasing incidental parr mortality) for an Atlantic salmon population with LGB support.

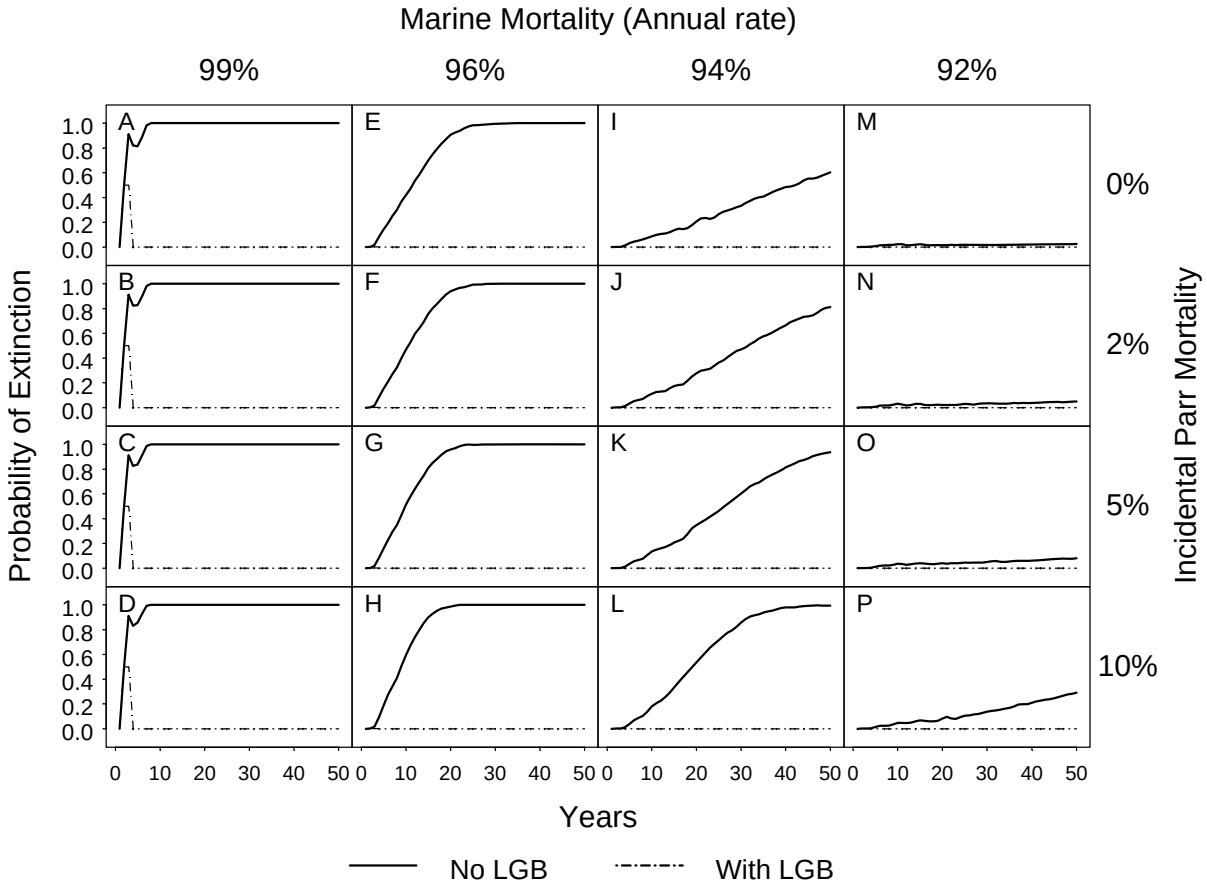


Figure 7.18. The probability of extinction under Scenario 4 (declining at-sea mortality and increasing incidental parr mortality) for an Atlantic salmon population with and without LGB support.

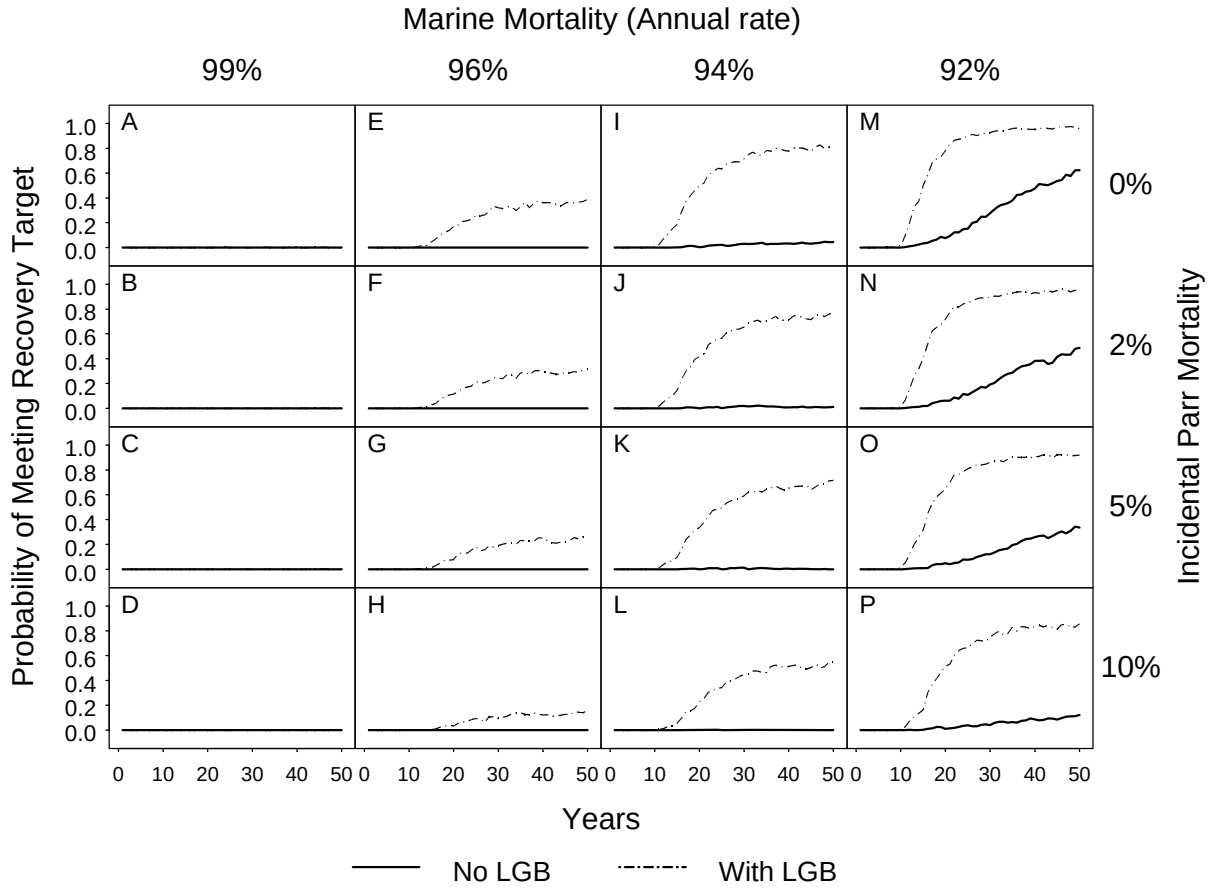


Figure 7.19. The probability of meeting the recovery target under Scenario 4 (declining at-sea mortality and increasing incidental parr mortality) for an Atlantic salmon population with and without LGB support.