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Research Document 2008/010

Document de recherche 2008/010

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Equilibrium analyses of the recovery feasibility of four Atlantic salmon (*Salmo salar*) in Nova Scotia and Southwest New Brunswick

Analyses de la taille à l'équilibre de quatre populations de saumon atlantique (*Salmo salar*) en Nouvelle-Écosse et dans le sud-ouest du Nouveau-Brunswick dans la perspective de leur rétablissement

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ISSN 1499-Q 848 (Printed / Imprimé)

Canada

FOREWORD

This document is a product from a workshop that was not conducted under the Department of Fisheries and Oceans (DFO) Science Advisory Process coordinated by the Canadian Science Advisory Secretariat (CSAS). However, it is being documented in the CSAS Research Document series as it presents some key scientific information related to the advisory process. It is one of a number of contributions first tabled at a DFO-SARCEP (Species at Risk Committee / *Comité sur les espèces en péril*) sponsored workshop in Moncton (February 2006) to begin the development of a 'Conservation Status Report' (CSR) for Atlantic salmon. When completed in 2007, the CSR could form the basis for a Committee on the Status of Endangered Wildlife in Canada (COSEWIC) status report, recovery potential assessment and recovery strategy, and most importantly, enable DFO to implement pre-emptive management measures prior to engagement in any listing process.

AVANT-PROPOS

Le présent document est issu d'un atelier qui ne faisait pas partie du processus consultatif scientifique du ministère des Pêches et des Océans, coordonné par le Secrétariat canadien de consultation scientifique (SCCS). Cependant, il est intégré à la collection de documents de recherche du SCCS car il présente certains renseignements scientifiques clés, liés au processus consultatif. Il fait partie des nombreuses contributions présentées au départ lors d'un atelier parrainé par le MPO-SARCEP (*Species at Risk Committee* / Comité sur les espèces en péril) à Moncton (février 2006) en vue de commencer l'élaboration d'un rapport sur la situation de la conservation du saumon atlantique. Lorsqu'il sera terminé, en 2007, ce rapport pourrait servir de base à un rapport de situation du Comité sur la situation des espèces en péril au Canada (COSEPAC), à une évaluation du potentiel de rétablissement et à un programme de rétablissement mais, avant tout, il permettra au MPO de mettre en œuvre des mesures de gestion anticipées avant même de s'engager dans un processus d'inscription.

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Correct citation for this publication:

Gibson, A.J.F., Jones, R.A, and Amiro, P.G. 2009. Equilibrium analyses of the recovery feasibility of four Atlantic salmon (*Salmo salar*) in Nova Scotia and Southwest New Brunswick. DFO Can. Sci. Advis. Sec. Res. Doc. 2008/010. xi + 40 p.

ABSTRACT

Four case studies are presented that illustrate the relationship between threats and recovery potential of salmon in the Atlantic Nova Scotia and Bay of Fundy sub-region. Equilibrium models are used to show the present status of each population, as well as the expected effect of recovery actions on the population. Equilibrium models split the life cycle of a species into two or more parts, and determine the population size at which the rates in each part of the life cycle are balanced, such that the population does not increase or decrease in size. By varying the life history parameters in a manner that represents the expected response to a human activity and examining the resulting change in equilibrium population size, the effects of the activity on the population can be evaluated in a way that places the expected response in the context of other threats to the population. The threats and stressors discussed in each case study are representative of the major types affecting salmon population viability in Bay of Fundy and Nova Scotia Atlantic coast rivers: acidification, hydroelectric development, low freshwater habitat productivity, and low at-sea survival.

The LaHave River (above Morgans Falls) case study was developed using data specific to this population and illustrates the effect of reduced at-sea survival on population viability. A freshwater production curve was derived using estimates of annual egg deposition and estimates of the number and age composition of smolts emigrating from this river. The lifetime egg production by smolts throughout their lives was estimated using return rate data, population-specific fecundities, and estimates of repeat spawning frequency. Return rates to LaHave River have averaged 2.37% (range: 1.09% to 4.33%) for salmon maturing after 1 winter at-sea and 0.48% (range: 0.24% to 0.97%) for salmon maturing after 2 winters at-sea. Presently, only low at-sea survival has been identified as a threat for this population. Opportunities to increase either freshwater productivity or capacity are limited, but could be expected to improve the potential for population recovery. At the lowest observed return rates, the population has an equilibrium size of zero; while at the average return rates, the equilibrium population size is roughly 1.1 million eggs, a value similar to recent egg depositions. If the high return rate observed in 1999 was maintained, the population would be expected to grow to a level above its conservation limit, and could support fishing activities.

The Big Salmon River case study, thought to be representative of the dynamics of endangered inner Bay of Fundy populations, was also based on population-specific data. Similar to the LaHave case study, the primary stressor to populations within this Conservation Unit (CU) is low at-sea survival, although other threats exist. The effect of decreased at-sea survival for the Big Salmon River population is a shift in the equilibrium population size from about 4 times the conservation egg requirement to a population that is not viable (equilibrium of zero). In the absence of human intervention or a change in at-sea survival, these populations are expected to become extirpated. In the past, population size was very sensitive to the amount of freshwater habitat; however, at present, increasing habitat quantity or quality is expected to have little to no effect on population size given present at-sea survival rates. Increasing at-sea survival, such that return rates are 4% for 1SW (1 sea winter) and 0.5% for 2SW (2 sea winters), results in a shift of the population equilibrium to about twice the conservation egg requirement. The case study illustrates how factors influencing one part of the life cycle, (in this

case at-sea survival) can limit the effectiveness of recovery actions focused on other parts of the life cycle (freshwater habitat restoration).

Interactions among multiple stressors are illustrated by the other 2 case studies presented. The salmon population in the Tobique River, New Brunswick, is under stress from reduced at-sea survival, but is further impacted by reduced survival of smolts as they migrate downstream past hydroelectric generating stations and through impoundments. Freshwater habitat productivity also appears low based on analyses of egg-to-smolt survival and juvenile abundance data undertaken as part of the case study. Given present freshwater production and at-sea survival, the population is not viable irrespective of the status of fish passage, even at the maximum observed return rates used in this analysis. If marine survival increased to a hypothesized (but plausible) 8% for 1SW and 3% for 2SW salmon, the population is still not viable at present passage survival rates, but a small equilibrium population size exists if fish passage is improved. If freshwater production is increased and marine survival increases, the population equilibrium is greater than the conservation requirement if fish passage survival is increased to 100%, but is less than half the requirement at present passage survival rates. Fish passage mortality. Therefore, has the potential to substantially limit the effectiveness of other recovery efforts, but addressing the fish passage survival issue alone is not expected to be sufficient to produce a viable population in this river.

A similar outcome was found in the West River (Sheet Harbour) case study. This river is impacted by both acidification and reduced at-sea survival. Low equilibrium population sizes can be obtained by addressing either threat, although long-term population viability in a randomly fluctuating environment is unknown. Based on the model results, both at-sea survival and acidification would have to be addressed to affect population recovery. These case studies illustrate that where multiple threats exist for a population, multiple responses are likely required to bring about recovery of the population.

RÉSUMÉ

Quatre études de cas sont présentées pour illustrer la relation qui existe entre les menaces et le potentiel de rétablissement du saumon dans la sous-région atlantique de la Nouvelle-Écosse et de la baie de Fundy. On a modélisé la taille à l'équilibre de chaque population afin d'illustrer leur état actuel ainsi que l'effet attendu des mesures de rétablissement prises. Les modèles utilisés divisent le cycle de vie des espèces en au moins deux parties et permettent de déterminer quelle est la taille de la population à laquelle les taux, dans chaque partie du cycle de vie, sont équilibrés de façon que la population ne voit pas son effectif s'accroître ou diminuer. En modifiant les paramètres du cycle biologique afin de représenter la réaction attendue à l'activité humaine et en examinant les changements ainsi obtenus dans la taille à l'équilibre de la population, on peut évaluer les effets qu'a l'activité sur la population d'une manière qui situe la réaction attendue dans le contexte des autres menaces pesant sur la population. Les menaces et les facteurs d'agression dont il est question dans chaque étude de cas sont représentatifs de certaines conditions affectant la viabilité des populations de saumon dans la baie de Fundy et dans les cours d'eau de la côte atlantique de la Nouvelle-Écosse : acidification, aménagements hydroélectriques, faible productivité des habitats d'eau douce et faible taux de survie en mer.

On a élaboré l'étude de cas sur la rivière LaHave (en amont de Morgans Falls) en utilisant des données propres à la population de ce cours d'eau. Cette étude de cas illustre l'effet d'un faible taux de survie en mer. Une courbe de production en eau douce a été calculée à l'aide d'estimations de la ponte annuelle, du nombre de saumoneaux qui émigrent de ce cours d'eau et de la composition selon l'âge de ces derniers. La production d'œufs sur toute la durée de vie des saumoneaux a été estimée à l'aide des données sur les taux de montaison et la fécondité propre à la population ainsi que d'estimations relatives à la fréquence du frai. Les taux de montaison dans la rivière LaHave se sont établis en moyenne à 2,37 % (fourchette de 1,09 à 4,33 %) pour les saumons unibermarins et à 0,48 % (fourchette de 0,24 à 0,97 %) pour les saumons dibermarins. Actuellement, seul le faible taux de survie en mer a été établi comme représentant une menace pour cette population. Les possibilités d'accroître tant la productivité en eau douce que la capacité des eaux douces sont limitées, mais devraient améliorer le rétablissement de la population. Aux taux de montaison les plus faibles observés, la population atteint une taille à l'équilibre de zéro, tandis qu'aux taux de montaison moyens, la taille à l'équilibre s'établit approximativement à 1,1 million d'œufs, une valeur similaire aux pontes récemment observées. Si le taux de montaison élevé qui a été observé en 1999 se maintenait, la population pourrait croître et atteindre des effectifs supérieurs à la limite propre à assurer la conservation des stocks, à laquelle les pêches pourraient être maintenues.

L'étude de cas portant sur la rivière Big Salmon, considérée comme représentative d'une population en voie de disparition de l'intérieur de la baie de Fundy, a également été fondée sur des données propres à la population. Même si d'autres menaces existent, le principal facteur de perturbation des populations présentes dans cette unité de conservation (UC) est également le faible taux de survie en mer. Ce faible taux de survie, dans le cas de la population de la rivière Big Salmon, se traduit par un changement dans la taille à équilibre de la population, laquelle est passée d'environ quatre fois les besoins en œufs propres à assurer la conservation des stocks à une population non viable (taille à l'équilibre de zéro). En l'absence d'intervention humaine ou d'une amélioration des taux de survie en mer, ces populations devraient disparaître. Par le passé, la taille de la population a été fortement tributaire de la disponibilité de l'habitat. Comme ce n'est plus le cas aujourd'hui, l'augmentation de la disponibilité et de la qualité de l'habitat devrait avoir peu d'effets, voire aucun, sur la taille de la population compte tenu des taux de survie en mer actuels. Une augmentation des taux de survie en mer se traduisant par une hausse des taux de montaison à 4 % pour les saumons unibermarins et à 0,5 % pour les saumons dibermarins entraînerait un changement dans la taille à l'équilibre de la population

équivalant à environ deux fois les besoins en œufs propres à assurer la conservation des stocks. L'étude de cas illustre de quelle façon les facteurs qui ont une incidence sur une partie du cycle de vie (dans le cas présent, le taux de survie en mer) peuvent limiter l'efficacité des mesures de rétablissement axées sur d'autres parties de ce même cycle de vie (restauration de l'habitat d'eau douce).

Les deux autres études de cas présentées illustrent les interactions qui existent entre divers facteurs de perturbation. La population de saumon de la rivière Tobique, au N.-B., subit également l'effet d'un faible taux de survie en mer, mais est davantage touchée par la survie réduite des saumoneaux qui, durant leur migration vers l'aval, doivent traverser des installations hydroélectriques et des ouvrages de retenue. La productivité de l'habitat d'eau douce semble également faible d'après des analyses de la survie entre le stade œuf et le stade saumoneau et des données sur l'abondance des juvéniles, lesquelles analyses ont été entreprises dans le cadre de l'étude de cas. Étant donné la production en eau douce et la survie en mer actuelles, la population n'est pas viable, quelle que soit la situation aux passages à poissons, même aux taux de montaison maximaux observés qui ont été utilisés dans la présente analyse. Si la survie en mer augmentait jusqu'à un niveau hypothétique (mais plausible) de 8 % pour les saumons unibermarins et de 3 % pour les saumons dibermarins, la population demeurerait non viable aux taux de survie actuellement observés aux passages. Toutefois, on obtient une faible taille à l'équilibre de la population si la situation est améliorée aux passages à poissons. Si la production en eau douce s'accroissait et que la survie en mer augmentait, la taille à l'équilibre de la population serait supérieure aux besoins propres à assurer la conservation des stocks si la survie aux passages des poissons était accrue à 100 %. Toutefois, cette taille à l'équilibre est inférieure à la moitié de ces besoins aux taux de survie aux passages actuels. La mortalité aux passages des poissons peut, par conséquent, limiter fortement l'efficacité potentielle d'autres initiatives de rétablissement. Par contre, le fait de s'attaquer au problème de la survie aux passages à poissons uniquement ne devrait pas être suffisant pour entraîner la production d'une population viable dans cette rivière.

Un résultat similaire a été observé dans l'étude de cas de la rivière West (Sheet Harbour) (Gibson *et al.*, 2007). Cette rivière est affectée par l'acidification, et sa population affiche un faible taux de survie en mer. On peut obtenir de faibles tailles à l'équilibre de la population en s'attaquant à l'une ou l'autre menace, même si la viabilité de la population dans un environnement fluctuant de façon aléatoire demeure inconnue. Selon les résultats du modèle, il faudra s'attaquer aux problèmes de la survie en mer et de l'acidification si l'on veut améliorer le rétablissement de la population. Ces études de cas illustrent qu'il faut vraisemblablement prendre de multiples mesures pour assurer le rétablissement de la population lorsque de multiples menaces pèsent sur cette dernière.

1. INTRODUCTION

Human activities have impacted upon salmon populations in the Bay of Fundy and Southern Upland regions of the Maritime Provinces for more than a century. Despite closures of both commercial and recreational fisheries, recent declines of populations in these regions have continued. At present, none of the assessed wild populations in this area are at more than 30% of their conservation spawner requirement, and declines of the wild component of all assessed populations exceed 80% in the last 15 years (Gibson et al. 2006).

Caron et al. (2006) identified 117 salmon rivers in salmon fishing areas (SFA's) 20 to 23, which includes all Bay of Fundy and Southern Upland rivers. Little information has been compiled for many of these rivers with respect to threats to their salmon populations, although some generalizations can be made for stressors in both freshwater and marine environments. Within the Bay of Fundy and along Nova Scotia's Atlantic Coast, survival rates of salmon at-sea are low and are a key determinant of risk within these areas. For example, Trzcinski et al. (2004) demonstrated that survival at-sea in an inner Bay of Fundy population was low enough, such that population replacement could not occur, and that these populations would go extinct in the absence of human intervention. At-sea survival is higher in outer Bay of Fundy and Southern Upland salmon populations, yet it is a key threat in these regions as well.

Although the extent of impact from dams and impoundments on Atlantic salmon has not been quantified, many rivers within these regions are developed for hydroelectric power generation. Fish passage is an issue that has not been addressed at some facilities, but others incorporate upstream passage and/or downstream diversion facilities to guide fish away from turbines.

Acidification is another major threat in Southern Upland rivers. Watt (1987) classified 48 of these rivers based on mean annual pH, and suggested that 14 had pH's below 4.7 and could not support salmon. A further 20 rivers had pH's between 4.7 and 5.1 and could only support remnant populations. Habitat status with respect to other characteristics is not well documented in these regions.

More than one threat or stressor exists for many salmon populations. Life history-based models provide mechanisms for evaluating how populations may be expected to respond to changes to these threats relative to other factors influencing their dynamics. In this Research Document, four case studies are presented that illustrate the effects on salmon population dynamics of the major threats listed above and show the magnitude of intervention that will be required to return populations to past abundance. Additionally, these examples provide a basis for a region-wide evaluation of recovery potential once the scope of the threats is quantified on a regional basis.

2. RELATIONSHIP BETWEEN THREATS AND RECOVERY POTENTIAL

In this section, we review the use of a modeling approach for evaluating how populations are expected to change in response to human activities. The analyses follow the approach detailed in Gibson et al. (*in press*) for Tobique River salmon. This is followed by four case studies that are used to illustrate the relationship between threats and recovery potential of salmon in this region: the Big Salmon River and the Tobique River in New Brunswick, and the LaHave River and West River (Sheet Harbour) in Nova Scotia. For each case study, an equilibrium model is constructed to show the present status of the population, as well as the expected effect of recovery actions on the population. The threats discussed in each case study are representative of ones that are affecting salmon population viability in Bay of Fundy and Nova Scotia Atlantic coast rivers. A full analysis of the data for the Tobique population is presented, followed by summaries from the other three case studies. Model equations are provided in the Tobique example (Gibson et al. *in press*).

2.1. Equilibrium Life History Models

Human activities can either directly (e.g. fishing) or indirectly (e.g. habitat alterations) alter some part of a fish population's life history. The affected life history parameters (e.g. fecundity, age- or stage-specific survival, age-at-maturity, or reproductive frequency) in turn affect the population's productivity. As a result, the effectiveness of recovery actions can be evaluated by examining how a population's productivity is expected to change in response to human-mediated actions.

Equilibrium modeling is one approach for evaluating the expected change. These models have been used for analyzing population dynamics (Moussalli and Hilborn 1986), for estimating biological reference points for fisheries management (Myers et al. 1995), for providing a basis for the estimation of the long-term consequences of mortality caused by pollution, dams, or other human activities (Barnthouse et al. 1988), and for linking fish habitat and fish population dynamics (Hayes et al. 1996). Equilibrium models split the life cycle of a species into 2 or more parts, and determine the population size at which the life history rates in each part of the life cycle are balanced, such that the population does not increase or decrease in size. By varying the life history parameters in a manner that represents the expected response to a human activity and examining the resulting change in equilibrium population size, the effects of the activity on the population can be evaluated in a way that places the expected response in the context of other threats to the population (Gibson et al. *in press*).

A natural split in the life cycle of Atlantic salmon is the smolt stage when fish are migrating to the marine environment. The first part of the equilibrium model describes freshwater production, which is the number of smolt produced as a function of egg deposition. The second part is the egg-per-smolt relationship, which gives the rate at which smolts are expected to produce eggs during their entire life. With the life cycle split into these two components, the model is analogous in a fisheries context to a spawner-recruit model and replacement line (or spawning biomass per recruit model).

The equilibrium approach is illustrated in Figure 2.1. In this example, the commonly used Beverton-Holt function is used to model smolt production in freshwater (Figure 2.1a). This model has 2 parameters: the slope of the function at the origin, which gives the maximum rate at which eggs survive to become smolts. This is based on the idea that survival is greatest when population sizes are very low, because competition between fish, which can result in reduced growth and increased mortality, is low. The second parameter is the carrying capacity of the river, which is the number of smolts that would be produced if egg deposition was extremely high. Changes in habitat quantity, say as a result of providing fish passage to areas that were previously inaccessible, have the effect of changing carrying capacity. Changes in habitat quality, say as a result of improving or reducing water quality, have the effect of changing the slope at the origin, but may change carrying capacity as well (Hayes et al. 1996).

As described by Gibson et al. (*in press*), a key assumption in these types of analyses is the timing of density dependence. In order for population regulation to occur (for an equilibrium to exist), density dependence must occur (Royama 1992). Here, density dependence is modeled via density-dependent survival in fresh water (the Beverton-Holt function). This is the equivalent of assuming that the carrying capacity of the freshwater habitat limits production and that, as a result of competition for limited resources, survival decreases as cohort size increases.

When modeling smolt production in fresh water, the parameters of the spawner-recruit (SR) function are expressed in units of smolts per egg. However, these are actually composite parameters that include survival from age-class to age-class (e.g. from eggs to age-0 (fry), from age-0 to age-1, etc.), as well as transition probabilities from parr to smolt (probability of smolting at age-1, at age-2, etc.). Thus, depending on the amount of data available or the nature of the threats or recovery actions, the complexity of the freshwater component of the equilibrium model can be increased or decreased as required, as is shown in the case studies.

The egg-per-recruit relationship (Figure 2.1b) is assumed to be density independent. This is to say that the rate at which smolts produce eggs throughout their lives does not depend on the number of smolts that are produced. This is the equivalent of assuming that resource availability in the marine environment is not limiting, and therefore mortality at-sea is not density-dependent. In contrast, resource availability in fresh water (see above), which determines carrying capacity, was assumed to limit the production of smolts. This paradigm is consistent with most population models for diadromous fish, and is further supported by a recent analysis of the timing of density dependence in Atlantic salmon, in which there was strong evidence for density dependence in fresh water and little evidence for density dependence within the marine environment (Gibson 2006). The rate at which smolts produce eggs is calculated based on the survival of immature salmon in the marine environment, age-at-maturity, fishing mortality, fecundity, and the number of times a fish spawns throughout its life.

The population equilibrium is found by pinpointing the egg and smolt abundance at which the production of smolts by eggs equals the reciprocal of the production of eggs by smolts (Figure 2.1c); note that graphically, this is the equivalent of exchanging the axes in 1b, so that the plots can be overlain. The equilibrium is the population size at which the population will stabilize if all model parameters do not fluctuate. Effects of human activities or other changes to population dynamics are evaluated by examining how the equilibrium changes in response to variation in the life history parameters resulting from the activity. In the example shown in Figure 2.1c, a decrease in smolt-to-adult survival shifts the equilibrium point to a smaller population size. If smolt-to-adult survival decreases far enough, the equilibrium population size goes to zero and the population will become extinct in the absence of human intervention or a change in 1 or more of the vital rates. However, an equilibrium population size greater than zero does not necessarily mean that a population is viable, because no allowance is made for random variability in the life history parameters.

Two key considerations when developing these kinds of models are the timing and nature of density dependence, as well as the identification of threats to a population. We use the meta-analysis of population regulation in salmon (Gibson 2006) as a guide for developing the model and for comparing life history parameter estimates with expectations based on other populations. Additionally, these kinds of meta-analyses are useful in order to assess whether the expected response to a recovery action is biologically plausible by providing a basis for comparison with other populations.

3. RECOVERY POTENTIAL OF TOBIQUE RIVER SALMON

The Tobique River is a tributary of the Saint John River, which is located upstream of Mactaquac Dam. The population in this river has undergone more than 3 decades of decline (Figure 3.1). The population is presently maintained by a stocking program under a Memorandum of Agreement signed in May 1968, between New Brunswick Electric Power Commission and Her Majesty the Queen, to maintain runs of salmon while at the same time producing electricity. Salmon smolts emigrating from the Tobique River need to bypass

3 hydroelectric generating stations: the Tobique Narrows Dam, Beechwood, and Mactaquac. Previous research has indicated that Atlantic salmon originating above the Tobique Narrows dam return to Mactaquac as adults, at a rate that is 54.7% of that of salmon originating at Mactaquac (Carr 2001, AMEC 2005). Based on coded-wire tag studies of survival of smolt released above Tobique, Beechwood, and Mactaquac dams, mortality is thought to be 24.7%, 13.6%, and 15.9% at these facilities, respectively. In addition to the threats posed by hydroelectric development, the Tobique salmon population is under stress from reduced at-sea survival, which is threatening other populations in the region, and potentially by low production in freshwater (see below).

The equilibrium analysis (based on the approach outlined in Section 2) presented in this section for the Tobique River was first completed by Gibson et al. (*in press*) and was used to evaluate how population size would be expected to change in response to changes in (1) survival during downstream migration, (2) at-sea survival, and (3) the quality of habitat. The first component of the equilibrium model (which gives the number of smolts produced as a function of egg deposition) used age- and stage-transition probabilities and mortalities to calculate parameter estimates. The second component was the egg per recruit (EPR) model, which gives the rate at which smolts produce eggs throughout their lives. Survival of emigrating smolts was included in the second component; i.e. the lifecycle is split at the start of migration (at the point of enumeration via the smolt wheel) and at spawning.

Data for Tobique River salmon include electrofishing surveys that provide densities of age-0 to age-2 and older parr, the adult age, sex, origin (hatchery or wild), and previous spawning history of salmon sampled at Mactaquac Dam and at counting facilities on Tobique River, estimates of the number of emigrating smolts by age obtained by sampling with a smolt wheel, and estimates of annual egg deposition. Because the origin and destination of salmon enumerated at Mactaquac Dam is unknown, the number of adult salmon destined to return to the Tobique River is not known. For these reasons, we obtain parameter estimates for the freshwater production model using population-specific data, whereas parameter values for the EPR model are obtained using both population-specific data, as well as information obtained from salmon in the Nashwaak River (a tributary downstream of Mactaquac Dam); a population for which smolt-to-adult return rates can be estimated.

Throughout this analysis, the focus is on wild production.

3.1. Smolt Production in Fresh water

Given the available data for Tobique River salmon, as well as the nature of the questions under investigation, the freshwater production model was split into its component parts. The model began with the annual egg deposition in the river, and used age-specific survival and smoltification probabilities to link egg deposition to smolt production (Gibson et al. *in press*).

Let $P_{t,0}$ be the number of age-0 parr in year t. The relationship between the number of age-0 parr in the spring and egg production during the previous fall is modeled as:

$$P_{t+1,0} = Q_t(1 - M^{\text{Egg}}),$$

where Q_t is the egg deposition in year t, and M^{Egg} is the combined mortality from the time of egg deposition until mid-summer, when the density of age-0 parr is estimated by electrofishing. M^{Egg} is assumed to be density independent.

Mortality between age-0 and age-1 was assumed to be density dependent, and a Beverton-Holt function was used to describe the nature of this density dependence. This is consistent with the analyses in Trzcinski et al. (2004), Gibson (2006), and Gibson et al. (*in press*). In this model, R_{asy} is the asymptotic density of age-1 parr (number per 100 m^2), and h is the number of 100 m^2 habitat units available to the population. Alpha (α) is the maximum survival rate between age-0 and age-1, which occurs at low population size where the slope of the Beverton-Holt function is steepest. We defined j_a as a vector containing the age-specific probability that a parr develops into a smolt at that age. The number of age-1 parr ($P_{t,1}$) is given by:

$$P_{t,1} = \frac{\alpha P_{t-1,0}}{1 + \frac{\alpha P_{t-1,0}}{R_{asy} h}} (1 - j_1)$$

The number of age-2 and older parr is determined by the number of parr in the cohort in the previous year, the annual mortality rate of parr, M^{Parr} (assumed density independent), and the probability of smoltification:

$$P_{t,a} = (P_{t-1,a-1})(1 - M^{\text{Parr}})(1 - j_a) \, .$$

Denoting the number of smolts in year *t* and of age *a* as $S_{t,a}$, the number of smolts produced by age would generally be given by 1 of 2 equations, depending on age:

$$S_{t,a} = \left\{ \begin{array}{ll} \frac{\alpha P_{t-1,0}}{1 + \frac{\alpha P_{t-1,0}}{R_{asy} h}} (j_1) & a = 1 \\ P_{t-1,a-1}(1 - M^{\text{Parr}})(j_a) & a = 2,3,4 \end{array} \right\} .$$

Wild age-1 smolts have not been observed in the Tobique River (see below), so the first equation is dropped from the model.

There is uncertainty in the egg depositions calculated for this population (see below and the discussion in Gibson et al. *in press*). As an alternative to treating these values as known without error, we estimated the egg deposition for each year from 1989 to 2004. This freshwater production model therefore contained 23 estimated parameters: $M^{egg}, M^{parr}, \alpha, R_{asy}, j_2, j_3 \text{ and } h$ (j_4 is set equal to 1) and 16 annual egg depositions. Estimates for these parameters were obtained by simultaneously fitting the model to the observed (or calculated, see below) egg depositions, juvenile densities, and smolt data, using maximum likelihood by minimizing an objective function ($O.F.V.$); that is the sum of the negative log likelihoods (Quinn and Deriso 1999) for the juvenile electrofishing data ($\ell_{electro}$), the smolt age-frequency data (ℓ_{age}^{smolt}), and the smolt count data (ℓ_{smolt}). Lognormal error structures (Myers et al. 1995) were used for all likelihoods except the smolt age-frequency data, for which a multinomial likelihood (Quinn and Deriso 1999) was used:

$$\ell_{electrofishing} = \sum_a \left(-n \ln \sigma_{elect} \sqrt{2\pi} - \sum_t P_{t,a}^{obs} - \frac{1}{2\sigma_{elect}^2} \sum_t (\ln P_{t,a}^{obs} - \ln P_{t,a})^2 \right)$$

$$\ell_{smolt} = -n \ln \sigma_{smolt} \sqrt{2\pi} - \sum_t S_t^{obs} - \frac{1}{2\sigma_{smolt}^2} \sum_t (\ln S_t^{obs} - \ln S_t)^2$$

$$\ell_{egg} = -n \ln \sigma_{egg} \sqrt{2\pi} - \sum_t Egg_t^{obs} - \frac{1}{2\sigma_{egg}^2} \sum_t (\ln Egg_t^{obs} - \ln Egg_t)^2$$

$$\ell_{age}^{smolt} = \sum_t \log \left(\frac{n_{smolt,t}!}{(x_{smolt,t,1}!)(x_{smolt,t,2}!).....(x_{smolt,t,r}!)} p_{smolt,t,1}^{x_{smolt,t,1}} ......p_{smolt,t,r}^{x_{smolt,t,r}} \right)$$

$$O.F.V. = -(\ell_{egg} + \ell_{smolt} + \ell_{electrofishing} + \ell_{age}^{smolt})$$

Gibson and Amiro (2003) had difficulty estimating the σ's for all model components. Following their approach, we used the average σ's obtained by Myers et al. (1995) for the spawner-recruit relationships for 15 populations and recruitment age categories for Atlantic salmon. For a recruitment age of 1, σ averaged 0.330 (n = 4; range: 0.293 to 0.402). Models were also fit to single data sets for recruitment ages of 0 and 2, for which σ was estimated as 0.334 and 0.581, respectively. These estimates were similar to the estimated σ's when smolt was used as the recruitment category (mean = 0.329; n = 5; range: 0.206 to 0.440). Based on these analyses, we set σ_a equal to 0.33 for all age categories.

The model was programmed using AD Model Builder (Fournier 1996). AD Model Builder uses the C++ auto-differentiation library for rapid fitting of complex non-linear models, has Bayesian and profile likelihood capabilities, and is designed specifically for fitting these types of models.

Egg Deposition

The numbers of wild and hatchery 1SW and MSW (multi-sea-winter) salmon contributing to egg deposition in the Tobique River, uncorrected for poaching, disease, removals, or hook and release mortality, are provided in Table 3.1 (from Gibson et al. *in press*). These data show a decrease in the total number of salmon counted at the Tobique Narrows fishway and trucked and released to the Tobique River from 1989 to present. The total number of eggs deposited to the Tobique River from 1989 to 1994 (Table 3.1) are taken from Appendix 1 of Marshall et al. (1997). Removals included salmon harvested from the recreational fisheries and native gillnet fisheries, as well as losses estimated from poaching, disease, and hook-and-release mortality (L. Marshall, *personal communication*). Removals from 1995 to 2004 were calculated in a similar manner, with the exception that no hook-and-release mortality estimates were done for the abbreviated recreational fisheries in 1996 and 1997. The resulting egg depositions also show a decreasing trend from the late 1980s to present, (Table 3.2; Figure 3.1) commensurate with an increased reliance on hatchery-origin fish to maintain the egg deposition (Figure 3.1). Model fits to the egg deposition data appear reasonable and are shown in Figure 3.2.

Juvenile Abundance

The densities of age-0, age-1, and age-2, and older juvenile salmon obtained by electrofishing are provided by site in Tables 3.3 to 3.5, respectively. Because not all sites were fished in all years, a standardized time series of juvenile densities was developed by fitting a generalized linear model including "site" and "year" effects to the data for each age group separately. The model was used to predict values for each site prior to calculating the annual mean densities. A comparison of the annual densities with the standardized values (Table 3.6) shows only minor differences in the values, but the fit of the statistical model to the standardized data is better (from Gibson et al. *in press*).

The standardized juvenile density series together with the model fits are shown in Figure 3.3 (from Gibson et al. *in press*). The data show declining trends in age-0 and age-2 and older densities from 1990 to present, whereas age-1 densities have remained relatively stable until the last few years. The model predicts declines in mean density in all 3 age classes. Scatterplots of the abundance of salmon within a cohort in sequential age classes (Figure 3.4; from Gibson et al. *in press*) show the asymptotic behaviour (characteristic of density dependence) for age-1 at relatively low densities of both age-0 and age-1 fish. Estimated relationships appear to fit the data reasonably.

Smolt Production

The number of smolts emigrating from the Tobique River annually (Table 3.7; from Gibson et al. *in press*) was estimated as the sum of the fall "pre-smolt" migration and the spring smolt migration. The fall pre-smolt numbers were determined by assuming that 64% of the total juvenile production emigrates during the fall period, as estimated by Jones et al. (2004) for the 2002 smolt class. Observed totals (2001 to 2005) range between 6,028 and 16,550 smolts per year, and are lower than those predicted by the model for the early 1990s (Figure 3.5). Smolt age data are collected by sampling smolts at several locations (Table 3.8). The values used to fit the model are the combined values from all counting devices. The age composition of the spring smolts appears consistent with the age composition of the pre-smolts captured the previous fall (Table 3.9).

Parameter Estimates

Parameter estimates for the freshwater production model are provided in Table 3.10. No convergence problems were detected by varying starting values and bounds. The results indicate low survival in fresh water relative to other populations (see below). Standard errors for all parameters are in the range of 5% to 50% of the estimate.

The parameter h links the juvenile densities estimated by electrofishing to the population size. Two options exist for this parameter. The number of habitat units (each habitat unit is 100 m^2) in the Tobique River with gradients greater than 0.12 has been estimated as 78,562 from orthophoto maps (Marshall et al. 1997). Assuming that the electrofishing surveys sample these habitats representatively, this value could be used as a constant in the model. An alternative approach is to estimate h within the model. In this case, h becomes the ratio of the density of each age class to the total abundance of this age class. This makes h a catchability coefficient, similar to those used for marine fish research surveys, and it can be interpreted as the number of habitat units that exist if all were occupied at the same density. The later approach was used here, and the estimated value of 21,700 is slightly less than a third of the number of habitat units estimated from the orthophoto maps.

3.1.1. Alternate Model Runs

As detailed in Gibson et al. (*in press*), we fit several alternate model formulations to the data, including: (1) egg depositions calculated using another method, (2) assuming the egg depositions were known without error, (3) using the un-standardized juvenile densities, (4) assuming the number of habitat units, *h*, was known to equal 78,562 units, and (5) several combinations of the above. Although parameter estimates differed slightly among the models, no deviations significant enough to change the conclusions herein were detected. The most significant deviation occurred when h was assumed to equal 78,562 habitat units. In this run, the egg to fry survival was higher and the survival of parr older than age-1 was lower. Overall freshwater production was slightly higher, although the fit to the smolt abundance data was poor (the model over estimated smolt abundance).

3.2. Egg Production by Smolts (The "EPR" Model)

The egg-per-recruit model includes terms for the probability of maturing at-sea age-1, size–specific fecundity, post-spawning survival (survival between spawning events), and passage survival of emigrating smolts (Gibson et al. *in press*). Fishing mortality is not included in the model, because all fisheries on this population are presently closed.

As previously mentioned, we consider a smolt to be a recruit in this analysis, and, consequently, make the break in the lifecycle between the early freshwater stages and the marine phase. The number of eggs produced by a smolt throughout its life is given by:

$$EPR = \sum_{c=1}^{2} Q_c \,, \qquad \text{where}$$

$$Q_1 = (1 - M^{pass})(1 - M^{\text{Sea}})(m_1) f_1 + \sum_{0}^{\max p} (1 - M^{\text{Adult}})^p f_2 \,,$$

$$Q_2 = (1 - M^{pass})(1 - M^{\text{Sea}})^c (1 - m_1) \sum_{0}^{\max p} (1 - M^{\text{Adult}})^p f_2 \,,$$

where *c* is the number of years spent at-sea prior to maturity, M^{pass} is the rate of mortality associated with downstream fish passage including turbine mortality, M^{Sea} the annual mortality of immature salmon at-sea, m_1 the probability of maturing after 1 winter at-sea, f_{c} the fecundity of first-time spawning 1SW (f_1) or older salmon (f_2), p the number of previous spawnings, and M^{Adult} is the adult annual mortality rate. As written above, all repeat spawning is sequential: the alternate repeat spawning strategy is not included in the model.

For the EPS model outlined above, 6 parameter values needed to be calculated from observed data: survival from smolt to sea-age 1, probability of maturing after 1 winter at-sea, survival of non-maturing salmon from sea-age 1 to sea-age 2, survival of post-spawning adults, and fecundities of small and large salmon.

Post-Smolt Survival and Probability of Maturing

Three parameters could potentially be used to describe survival at-sea and maturity, whereas the data consists of only 2 observations: the proportion of salmon that return after 1 winter at-sea and the proportion that return after 2 winters at-sea. A simplifying assumption is therefore needed for this model component. Here, we use the approach of Gibson et al. (*in press*) and assume that the survival rate for immature salmon is the same during both their first year and second year at-sea. We can then use return rates of 1SW and 2SW salmon to calculate the probability of maturing after 1 winter at-sea and survival from smolt to sea-age 1.

At present, return rates cannot be estimated from the Tobique River salmon data, because both the tributary of origin and destination of released fish are unknown (due to the confounding effects of trucking and releasing adult salmon above the Mactaquac dam). Therefore, we use the return rates for Nashwaak River (also in the Saint John River watershed) to derive parameters for this model component. For the smolt year classes of 1998 to 2003, percent returns ranged between 1.5% and 6.4% for 1SW salmon and between 0.3% and 1.6% for 2SW salmon (Table 3.11; from Gibson et al. *in press*). Average rates were 3.2% and 0.9% for 1SW and 2SW salmon, respectively. Given the above assumption, these values equate to a survival rate of 0.113 for immature salmon and a probability of maturing after 1 year at-sea of 0.286. The highest return rates observed for the Nashwaak River (0.064 for 1SW and 0.016 for 2SW) equate to a survival rate of 0.161 and a probability of maturing of 0.395.

Post-Spawning Survival, Repeat Spawning and Fecundities

Again, without knowing the number of salmon bypassing Mactaquac that are destined for the Tobique River each year, post-spawning adult mortality cannot be calculated. In this case, extrapolation from the Nashwaak River is less applicable due to expected difference in survival of downstream migrating adults as a result of passage at hydroelectric facilities. Of the 43,109 wild salmon released into Tobique River that were aged, 42,350 were first-time spawners, 730 had spawned once previously, 30 had spawned twice previously (Table 3.12; from Gibson et al. *in press*). Assuming these values are representative of the population, the average annual survival for post-spawning adults is 0.029. For comparison, the average annual survival for post-spawning adults on the Nashwaak River (1993 to 2002) is 0.133.

For the years 1985 to 2004, fecundity of female salmon averaged 3,654 eggs per fish for small salmon and 6,975 eggs per fish for large salmon, using the length-fecundity relationship developed by Marshall and Penney (1983) for Saint John River salmon. During this time, the proportion of female salmon averaged 0.085 for small and 0.929 for large. Therefore, the model inputs for fecundity are 311 eggs per small salmon and 6,479 per large salmon.

Based on the above values and assuming a passage survival of 1.0, a smolt is expected to produce 77 eggs throughout its life. At a passage survival rate of 0.547 (AMEC 2005, Carr 2001), the lifetime egg production of a smolt is 38.5 eggs.

3.3. Equilibrium Analyses

The equations below correspond to the analysis described in Section 2.1. Population equilibriums were found by combining the 2 model components described in sections 3.1 and 3.2, resulting in a deterministic model which corresponds to the population size at which all model parameters do not change.

Given the model components above, the equilibrium analysis proceeds as follows:

For a given value of M^{Pass} (or some other control variable), the number of eggs produced by the number of smolts in year t is:

$$Eggs = EPR_{M^{Pass}} S \ .$$

Equilibrium numbers of eggs and recruitment levels (denoted with asterisks) are found by solving this equation for *S* and substituting the result in the freshwater production model (Quinn and Deriso 1999):

$$\frac{Eggs^*}{EPR_{M^{Pass}}} = \frac{\breve{\alpha} Eggs^*}{1 + \frac{\breve{\alpha} Eggs^*}{\breve{R}_{asy}}} \ .$$

Note that here, $\breve{\alpha} \text{ and } \breve{R}_{asy}$ are the rescaled parameters (using the other model parameters) to represent the maximum survival to smolt and the asymptotic recruitment level for smolt. The equilibrium spawning biomass ($Eggs^*$) is then:

$$Eggs^* = \frac{\left(\breve{\alpha} EPR_{M^{Pass}} - 1\right)\breve{R}_{asy}}{\breve{\alpha}} \ ,$$

and the equilibrium number of smolts (S^*) is found by substituting the $Eggs^*$ into the freshwater production model:

$$S^* = \frac{\breve{\alpha} Eggs^*}{1 + \frac{\breve{\alpha} Eggs^*}{\breve{R}_{asy}}} \ .$$

The rescaled freshwater production model provides 2 parameter estimates of interest: the maximum number of smolts per egg and the asymptotic level for smolt production. For comparison, both of these values are low relative to the Big Salmon River population (Table 3.13). At the estimated maximum number of smolts per egg (0.0046), a smolt would have to produce more than 217 eggs throughout its life for the population to have an equilibrium population size greater than zero.

The potential for recovery of Tobique River salmon is shown graphically in Figure 3.6 (reprinted from Gibson et al. *in press*) for 2 fish passage scenarios. Given present freshwater production and at-sea survival, the population is not viable irrespective of the status of fish passage, even at the maximum observed return rates used in this analysis. If marine survival increases to a hypothesized 8% for 1SW and 3% for 2SW salmon, the population is still not viable at present passage survival rates, but a small equilibrium population size exists if fish passage is improved. If freshwater production is increased, the population equilibrium is greater than the conservation requirement when fish passage survival is increased to 100%, but is less than half the requirement at present passage survival rates. Fish passage mortality therefore has the potential to substantially limit the effectiveness of other recovery efforts, but addressing the fish passage survival issue in and of itself is not expected to be sufficient to produce viable populations.

The low freshwater production estimates produced here are a bit disconcerting given past salmon production in this river. Evidence for higher freshwater production comes from both the early electrofishing data and the estimates of smolt abundance. If production is being underestimated by these models, the true curve likely falls between the 2 scenarios presented in Figure 3.6, and, thus, the potential outcomes are bracketed by these scenarios. Two potential issues are identified: the low estimated carrying capacity for age-1 parr, and the low survival of age-1 and older parr. Resolving whether freshwater production is low, and if demonstrated to be so, establishing the reasons why should be a research priority for this river. Current research on smolt migration should help confirm whether smolt abundance is being underestimated due to migration of smolt during the fall, a factor that could incorrectly inflate the age-1 and older parr mortality estimate.

4. POTENTIAL FOR RECOVERY OF LAHAVE RIVER SALMON

The salmon population in the LaHave River (above Morgan Falls) has undergone declines of more than 75% over the last 3 generations (Gibson et al. 2006), and is presently at about 45% its conservation egg requirement (Amiro et al. 2006). This population increased rapidly in size during the early 1970s, after construction of a fishway at Morgan Falls. This trajectory is shown in a spawner-recruit space in Figure 4.1. Egg deposition in the late 1980s remained high despite decreasing recruitment, due in part to the time lags between egg deposition and maturation, as well as more restrictive fisheries management. Both recruitment and egg deposition declined during the 1990s, as a result of low survival at-sea. For the 1996 to 2004 smolt year classes (Table 4.1), return rates of salmon to Morgan Falls on the LaHave River have averaged 2.37% (range: 1.09% to 4.33%) for salmon maturing after 1 winter at-sea and 0.48% (range: 0.24% to 0.97%) for salmon maturing after 2 winters at-sea (Gibson and Amiro 2007). This low survival is the only threat presently identified for this population.

To evaluate recovery potential for LaHave River salmon, we used the model formulation presented in Section 3, in which the population dynamics are modeled using an egg-to-smolt freshwater production model coupled with a model giving the number of eggs produced by a smolt during its life (EPS model). For this river, estimates of annual egg deposition are available for the period from 1973 to 2005, and estimates of the number and age composition of smolts emigrating from this river are available for the years 1996 to 2005.

A freshwater production curve for this river is shown together with the curves from 3 other rivers in the Maritime Provinces: the Big Salmon, the Nashwaak, and the Tobique in Figure 4.2. With the exception of Big Salmon River, all of the observed data have been obtained at low spawner abundance, making estimation of carrying capacity difficult and potentially inaccurate. In the case of the LaHave River, the carrying capacity is estimated as 1.36 smolts per habitat unit, which is in the range values for the other rivers, but is low in comparison with some older estimates. For example, the value of 3.8 smolts per 100 m^2 is sometimes used as a reference value for Atlantic salmon (Symons 1979). The estimate of the maximum survival rate from egg-to-smolt of 0.02 (or 2 smolts for every 100 eggs) is similar to the value obtained for the Big Salmon River, but is an order of magnitude higher than those obtained for the other 2 rivers. This value is evidence of relatively good freshwater habitat and is one of the reasons that habitat quality is not considered a primary threat for this population.

Amiro et al. (2006 – Table 17) provide the sex ratios and fecundities estimated for salmon in the LaHave River in 2005. Using these values, a 1SW salmon is expected to contribute 1,652 eggs and a 2SW or MSW salmon is expected to contribute 5,664 eggs. Using the smolt-to-adult return rates given above, and assuming consecutive spawnings with a post-spawning survival rate of 10% between spawnings and a maximum of 3 spawning events, the expected number of eggs produced by a smolt throughout its life is calculated as 84.2 eggs (range: 39.3 - to 170.9 eggs, based on the range of return rate estimates). The replacement lines derived from these values are shown overlain on the freshwater production curve in Figure 4.3. At the lowest return rates, the population has an equilibrium size of zero; while at the average return rates, the equilibrium population size is roughly 1.1 million eggs. At the maximum return rates observed by Symons (1979), the population would be well above its conservation limit. The observed egg-to-smolt data points are all near the equilibrium population size as would be expected if the model and data inputs were reasonably approximating the population's present dynamics.

5. RECOVERY POTENTIAL OF BIG SALMON RIVER ATLANTIC SALMON

Trzcinski et al. (2004) used a life history-based equilibrium model to analyze the dynamics of inner Bay of Fundy Atlantic salmon (iBoF) in order to determine if the probability of persistence of iBoF salmon is sensitive to changes in habitat quantity and quality, and to determine the relative influence of various life history parameters on its probability of persistence. They used data from Big Salmon River, including recreational fishery catch and effort data, counts of adults at a counting fence, counts of adults obtained from shoreline observation and dive surveys, redd (egg nests) counts, juvenile density data obtained by electrofishing surveys, estimates of the number of migrating smolts, and age-frequency data for both smolts and adults. They estimated survival rates and stage transition probabilities (probability of smolting by age and probability of maturing by age) using a freshwater production model similar to the one used here for Tobique River salmon. They compared 3 models: 1 in which the dynamics did not change through time, 1 in which the life history parameters relating to freshwater production were allowed to change through time, and 1 in which the life history parameters relating to survival at-sea and maturation were allowed to change through time. They concluded that the model with a change in the marine life history parameters provided the best fit to the data. Similar to both Tobique River and LaHave River salmon, low survival at-sea is placing inner Bay of Fundy populations at risk. Trzcinski et al. (2004) used a step function to estimate survival at-sea for 2 time periods. Although the model demonstrates the effects of increased mortality at-sea, the use of the step function underestimates the extent of the problem. Gibson and Bryan (in prep.) extended the analysis to estimate annual survival at-sea and found that, from 2001 to 2004, return rates averaged 1.4% for 1SW salmon and <0.1% for 2SW salmon; values about half those estimated by Trzcinski et al. (2004). Gibson and Bryan's estimates of the average return rates for the 1967 to 1971 smolt years are 6.1% for 1SW salmon and 0.2% for 2SW salmon. Annual mortality of post-spawning adult salmon is estimated to have changed from 0.495 to 0.643. Further details of the data and model are available in Trzcinski et al. (2004).

Both the analyses of Trzcinski et al. (2004) and a meta-analysis of the survival of juvenile salmon in freshwater (Gibson 2006) indicate that habitat quality in Big Salmon River remains very good. Further evidence to support this position comes from the observed survival of hatchery-reared fry that are released into the river (Flanagan et al. 2006).

An equilibrium analysis of potential recovery actions for Big Salmon River salmon, using the full model presented in Section 3, is summarized in Figure 5.1. Model parameters are based on Gibson and Bryan's return rate and post-spawning mortality estimates and the freshwater survival and smoltification probabilities given in Table 3.13. The top panel of Figure 5.1 illustrates the predicted change in dynamics from the past time period (late 1960s to early 1970s) to present (2001 - 2004). The effect of decreased at-sea survival is a shift in the equilibrium population size from about 4 times the conservation egg requirement to a population that is not viable (equilibrium of zero). In the past, population size was very sensitive to habitat quantity (Figure 5.1, middle panel). However, at present, increasing habitat quantity or quality will have little to no effect on population size given present at-sea survival rates. Increasing at-sea survival, such that return rates are 4% for 1SW and 0.5% for 2SW, results in a shift of the population equilibrium to about twice the conservation egg requirement (Figure 5.1, bottom panel). Trzcinski et al. (2004) demonstrate that the population equilibrium is not very sensitive to other life history parameters, and that past abundances cannot realistically be achieved without an increase in survival at-sea. It is important to note that these results do not indicate that freshwater habitat is unimportant. Clearly, if these populations are to recover, a sufficient amount of freshwater habitat will be required to support the populations. The recovery potential of this population is dependent on the continued capacity of the freshwater habitat to support a healthy population.

6. RECOVERY POTENTIAL FOR AN ACIDIFIED RIVER: WEST RIVER (SHEET HARBOUR)

Many rivers in Nova Scotia’s Southern Upland region have been negatively impacted by acid rain. An example is West River on Nova Scotia’s Eastern Shore. There are about 16,672 habitat units available in this river, leading to a conservation spawner requirement of just over 4 million eggs. This is a large watershed, representing about 7% of the egg requirement for all of SFA 20 (O’Connell et al. 1997). There is relatively little information about the life history characteristics of its salmon population, but based on the life history characteristics of the nearby Liscomb River salmon, the expected egg deposition would come from about 1,163 small and 132 large salmon. As well as being impacted by low pH, the population is almost certainly being negatively impacted by the low survival at-sea being experienced by other populations in the region. Presently, the river is being limed at a single location, which is expected to increase pH in about 5,000 of the 16,672 habitat units.

An impediment to evaluating the expected response of this population to recovery actions is the paucity of data about the population and river in either an acidified or treated state. This problem can be overcome by assuming that the dynamics of the population are similar to those of other populations in the area. One well-studied Southern Upland population that is only slightly impacted by acidification is the LaHave River population, and an equilibrium model based on the LaHave data could be assumed to represent an un-acidified production scenario for all populations on the Nova Scotia Atlantic Coast. We base the following analysis on that assumption.

While the above could be assumed to represent the dynamics of a salmon population inhabiting a non-acidified river, development of the acidified case is a bit more problematic. Based on measured pH values, Lacroix and Knox (2005) estimated that mortality would be high in about 85-90% of West River, and that some mortality due to pH would be expected in the remaining areas. In the 1994 Draft Management Plan for East/West river salmon, it was concluded that the loss of juvenile production due to pH was about 80%. For the purposes of this analysis, we assumed that the maximum survival rate from egg to smolt was the same as that of the LaHave River population (based on the idea that there may be some small, unaffected areas that could sustain populations), but that the average per unit carrying capacity was 15% that of the LaHave population on a per unit area basis. Although the lime doser currently in place in West River will treat about 5,000 habitat units, for illustrative purposes we present a scenario where the entire river is pH recovered.

The freshwater production curve for the acidified condition is shown, together with the replacements lines from the LaHave River in Figure 6.1a. Populations are not viable in this scenario, even at the maximum survival rates observed on the LaHave River from 1996 to 2004. Figure 6.1b shows the expected change in dynamics if freshwater production is improved to the level observed in the LaHave River. Deterministic equilibriums exist at smolt-to-adult return rates above the average observed, but the equilibrium population sizes are low, and are likely small enough that the population would be at risk of extinction from random variability in either environmental or demographic processes, or from genetic effects at small population sizes. A hypothetical improvement in marine survival to return rates of 6% for 1SW and 2% for 2SW salmon is added to the plot in Figure 6.1c, showing that increases in marine survival to this level in the absence of improvements to water quality do not result in a viable population. Figure 6.1d shows the resulting equilibrium if both marine survival and water quality issues are addressed on this river, a scenario in which the conservation egg requirement is reached.

It is important to note that both the acidified and recovered scenarios are extrapolated from other populations. As a result, these models show the direction and approximate magnitude of the response, but should not be used to evaluate the exact magnitude of the response without a more thorough examination of the input values. That being said, the reduced survival in the marine environment, which is the limiting factor in all examples presented here, is widespread and minor changes to the input values should not alter the conclusion that it has the capacity to limit population recovery. Further empirical evidence is provided by the observation that none of the rivers within this area are meeting their conservation spawner requirements irrespective of their status with respect to pH (Gibson 2006).

7. SUMMARY AND CONCLUSIONS

The equilibrium models presented here can be used to identify the expected population response to recovery activities or to changes in life history parameters for other reasons. However, two major impediments exist for determining the recovery potential of Bay of Fundy and Southern Upland salmon on a regional basis. This first is the lack of a comprehensive list of threats to populations on a river-by-river basis that can be used to evaluate recovery potential on a regional scale. While the modeling approaches presented here can be used to evaluate the activities required for recovery on a population-specific basis, in the absence of an evaluation of the extent of the threats, the magnitude of the effort required to affect recovery is unknown.

Secondly, the models used here assume that abundance within populations is sufficient that a response to recovery actions is possible. Juvenile salmon were not found in 28 of 57 rivers sampled during an electrofishing survey on the Southern Upland in 2000, and 16 of the 29 rivers with juvenile salmon had fewer than 5.0 juvenile salmon per 100 m^2, suggesting that many populations are extirpated or are critically low. Electrofishing surveys on monitored rivers (the LaHave River and St. Mary’s River) indicate declining juvenile abundance since 2000. At present, the number of rivers with sufficient abundance of salmon for recovery to occur is not known, but could be determined by repeating the electrofishing survey of 2000. Within the inner Bay of Fundy, a key rescue activity was the development of a Live Gene Bank to harbour and protect the remaining genetic diversity within the remaining populations. At the time this effort was initiated, only a few populations remained within the inner Bay with sufficient abundance and genetic diversity such that Live Gene Banking was feasible (Gibson et al. 2004). For these reasons, both the identification of larger residual populations and the identification of threats to populations should be research priorities in these regions. If current trends continue, actions will have to be timely to be effective.

A recurring theme in the 4 case studies presented herein is the limiting effect of reduced at-sea survival on the recovery potential of Atlantic salmon. While at present the source or sources of the mortality is not known, recovery activities that are focused in fresh water have the potential to slow population decline or to maintain populations at low levels, until such time as the cause of low at-sea survival is identified and mitigated. However, none of the case studies were examples where populations would be expected to increase without an increase in survival at-sea. Research in this area is therefore a priority, either through the use of tagging and tracking studies or analyses of existing data to determine covariates with survival at-sea that may help identify the cause of its decline. On a very preliminary positive note, return rates of 1SW salmon to some monitored rivers in the Bay of Fundy and Southern Uplands were up in 2006.

Acidification is another major threat within the Southern Upland. Soils are shallow, often underlain by acidic slates, and water draining these soils generally lacks base minerals. Sixty-five rivers in this region are thought to have historically supported salmon runs, of which about 42 rivers have recorded salmon catches. Watt (1987) classified 48 of these rivers based on mean annual pH and suggested that 14 had pH’s below 4.7 and were extirpated of salmon, and a further 20 rivers had pH’s between 4.7 and 5.1 and could only support remnant populations. Habitat status with respect to other characteristics in this region is largely unknown and is not being monitored. Meta-analyses of survival rates of populations for which there is data (e.g. Gibson 2006) provides an alternative test of habitat quality through an examination of the fishes’ response to its environment. These types of analyses also provide a baseline of acceptable values against which the vital rates of a population under study can be compared, thereby, helping to focus research and recovery efforts.

Populations increase or decrease in size in response to changes in life history parameters resulting from either human activities or some other factor. As illustrated by the four case studies, the response of a population to a given recovery action depends not only on the recovery action, but on other threats to the population as well. For example, when fish habitat quality is compromised (such as that in the West River example) higher lifetime production of eggs by smolts is required to offset the resulting loss of freshwater productivity. At times, the required increase may be outside of the range of values observed in the species if past abundances are to be attained. Although this type of analysis suggests that high adult abundance is unlikely to occur as a result of increased freshwater production alone, the converse also holds true: in the absence of good freshwater habitat, populations would not be expected to reach past abundances even if smolt-to-adult return rates increased. Where multiple threats exist for a population, multiple responses to these threats are likely required to bring about recovery of the population.

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Table 3.1. The total number of wild and hatchery origin salmon counted at the Tobique Narrows fishway or trucked and released in the Tobique River, NB, from 1989 to 2004 (from Gibson et al. *in press*).

	One Sea Winter			Multi-Sea Winter			
Year	Hatchery	Wild	1SW Total	Wild	Hatchery	MSW Total	Grand Total
1989	568	4,991	5,559	147	2,315	2,462	8,021
1990	906	4,044	4,950	519	2,314	2,833	7,783
1991	1,314	3,650	4,964	391	2,686	3,077	8,041
1992	871	3,329	4,200	436	2,465	2,901	7,101
1993	587	1,813	2,400	233	1,709	1,942	4,342
1994	721	1,291	2,012	320	1,106	1,426	3,438
1995	1,906	1,956	3,862	330	1,187	1,517	5,379
1996	2,500	994	3,494	388	1,479	1,867	5,361
1997	1,961	188	2,149	373	823	1,196	3,345
1998	3,014	296	3,310	347	184	531	3,841
1999	1,427	352	1,779	405	440	845	2,624
2000	763	1,167	1,930	97	167	264	2,194
2001	613	458	1,071	219	304	523	1,594
2002	820	432	1,252	48	54	102	1,354
2003	463	235	698	235	120	355	1,053
2004	149	378	527	99	182	281	808

Table 3.2. Estimated egg deposition by wild and hatchery-origin salmon in the Tobique River, NB, from 1989 to 2004.

Year	Wild	Hatchery	Total
1989	16,263,620	1,251,290	17,514,910
1990	14,737,154	1,701,368	16,438,522
1991	15,966,556	1,614,448	17,581,004
1992	14,023,899	4,095,299	18,119,198
1993	9,891,213	655,501	10,546,714
1994	7,317,655	1,642,803	8,960,458
1995	8,606,109	1,358,836	9,964,945
1996	9,899,543	1,798,573	11,698,117
1997	6,250,143	891,570	7,141,713
1998	3,255,733	1,011,207	4,266,939
1999	4,063,143	1,331,913	5,395,056
2000	1,667,522	620,365	2,287,887
2001	1,884,926	1,088,789	2,973,715
2002	275,881	697,371	973,252
2003	1,137,178	1,184,293	2,321,471
2004	1,143,487	686,269	1,829,756

Table 3.3. Densities of age-0 parr by site and year in the Tobique River, NB, estimated by electrofishing from 1979 to 2004.

	Site Number																			
Year	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20
1979	48.7	39.5	.	61.6	0.3	10.4	30.3	.	11.7	.	.	.	0.0	.	.	.	.	.	.	.
1980	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1981	75.5	39.9	47.4	188.1	63.3	131.2	.	.	.	25.2	65.7	69.7	55.0	21.3	.	.	.	.	.	.
1982	23.3	3.6	0.0	40.0	16.4	11.7	118.3	5.4	18.8	6.5	12.8	15.9	23.2	3.8	6.3	.	.	.	.	.
1983	4.7	2.1	0.0	43.9	1.5	23.7	31.4	0.0	3.3	4.5	16.2	5.0	0.0	9.0	5.2	.	.	.	.	.
1984	0.9	8.1	0.0	23.7	0.0	8.3	.	6.4	116.1	2.3	14.7	0.6	0.0	1.7	0.0	.	.	.	.	.
1985	76.7	44.8	0.8	40.6	0.0	176.4	93.4	.	12.9	58.0	9.4	0.0	0.0	6.3	0.3	0.7	.	.	.	.
1986	25.9	26.8	0.0	0.0	1.1	78.2	23.6	.	34.5	0.0	10.2	0.0	0.0	27.1	1.3	0.0	.	.	.	.
1987	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1988	.	.	.	.	.	.	103.2	.	19.0	8.8	93.0	.	.	49.6	.	.	.	.	.	.
1989	.	.	.	.	.	.	40.2	.	18.2	2.3	1.4	.	.	0.0	.	.	.	.	.	.
1990	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1991	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1992	1.2	0.4	0.8	.	.	.	53.9	.	57.1	22.3	17.0	.	.	13.3	.	.	.	.	.	.
1993	.	2.7	43.5	.	.	.	0.0	.	29.9	77.8	40.6	.	.	35.1	.	.	1.7	15.7	.	0.0
1994	.	.	0.0	.	.	.	0.0	.	18.8	12.1	0.0	.	.	66.5	.	.	.	0.0	0.0	0.0
1995	.	.	154.5	1.8	.	.	34.9	.	0.0	42.5	6.6	.	.	32.7	.	.	.	9.9	34.6	0.0
1996	0.0	18.8	0.0	0.0	0.0	.	35.5	0.4	19.0	7.9	0.0	1.0	0.4	13.6	0.6	.	18.2	0.0	0.0	0.0
1997	3.9	23.9	0.0	24.7	9.2	.	16.5	55.3	9.7	21.3	.	.	0.0	6.7	2.7	.	13.4	9.1	40.0	0.0
1998	10.2	22.1	0.0	0.0	0.0	.	72.6	13.7	25.3	3.2	.	.	0.0	4.8	3.5	20.0	0.0	0.0	0.0	0.0
1999	1.7	24.1	0.0	3.1	0.0	.	44.1	7.5	17.4	8.1	.	.	11.6	18.6	2.3	4.8	0.0	0.0	0.0	0.0
2000	4.2	10.4	5.6	25.4	0.4	.	26.2	8.0	3.9	0.7	.	.	60.7	26.5	18.2	14.9	.	0.0	24.4	0.0
2001	3.5	62.2	0.0	5.9	0.0	.	23.8	8.8	14.9	0.0	.	.	0.6	1.0	0.0	7.9	0.0	.	0.0	0.0
2002	0.0	4.8	0.0	12.5	0.0	.	36.3	0.0	6.3	0.5	.	.	0.0	4.7	1.0	13.7	.	.	.	.
2003	0.0	0.6	0.0	0.0	0.0	.	5.7	0.6	2.5	0.6	.	.	0.0	0.0	0.0	0.0	0.0	0.2	.	0.0
2004	0.0	6.1	0.0	0.6	0.4	.	28.6	0.0	21.9	12.9	.	.	0.0	11.7	2.5	4.7	58.3	0.6	.	0.6

Note: Values from 1990 to present were obtained by mark-recapture or spot checks assuming the catchability of age-0 parr is 0.837 times that of age-1 parr. This constant is the ratio of the age-0 to age-1 catchabilities for the pre-1990 sites when depletion methods were used.

Table 3.4. Densities of age-1 parr by site and year in the Tobique River, NB, estimated by electrofishing from 1979 to 2004.

	Site Number																			
Year	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20
1979	7.4	4.8	.	64.4	8.9	12.6	5.1	.	8.0	.	.	.	13.7	.	.	.	.	.	.	.
1980	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1981	7.6	3.5	21.5	21.0	0.7	9.9				10.2	3.9	0.0	11.1	0.0			.	.	.	.
1982	8.3	3.8	22.6	27.0	1.7	12.1	20.1	2.5	14.1	4.7	2.9	0.0	17.4	2.3	1.1		.	.	.	.
1983	0.7	1.0	3.6	22.3	1.4	5.8	3.8	6.7	0.3	2.2	0.2	0.0	9.6	0.5	0.7		.	.	.	.
1984	0.5	3.0	0.6	9.7	3.0	2.6		0.3	11.7	0.0	0.4	0.0	3.2	0.7	0.0		.	.	.	.
1985	2.1	3.3	1.9	14.2	0.7	5.1	2.1		6.5	8.7	0.2	0.0	9.6	0.8	0.3	4.2	.	.	.	.
1986	9.6	15.7	9.9	20.9	6.1	22.7	11.1		5.0	8.6	0.9	0.0	17.0	0.0	0.3	31.9	.	.	.	.
1987						.					.	.					.	.	.	.
1988						.	5.2		5.3	6.7	2.4	.		0.8			.	.	.	.
1989						.	7.2		15.7	12.8	3.4	.		0.9			.	.	.	.
1990						.					.	.					.	.	.	.
1991						.					.	.					.	.	.	.
1992	0.2	0.1	9.7			.	1.3		18.1	10.9	2.3	.		0.4			.	.	.	.
1993		2.5	6.8			.	0.0		17.6	18.2	7.6	.		0.3			2.6	2.7	.	4.0
1994			11.6			.	0.0		1.4	6.3	0.1	.		3.1			.	2.0	8.6	2.7
1995			3.3	13.4		.	17.9		0.0	19.4	2.5	.		0.0			.	1.2	2.2	2.7
1996	6.0	4.5	8.2	4.2	1.5	.	3.0	8.4	10.2	5.0	0.7	0.0	5.9	0.5	2.6		2.4	8.0	5.4	2.1
1997	5.1	7.7	0.9	6.6	4.3	.	3.5	3.7	6.8	6.7	.	.	5.9	1.2	3.6		0.3	10.3	2.1	3.3
1998	2.6	8.1	1.9	8.6	4.2	.	9.9	15.4	15.5	11.7	.	.	9.6	0.6	2.4	10.0	10.3	2.2	10.0	14.8
1999	1.9	6.4	1.6	4.1	5.7	.	9.2	5.4	15.7	7.1	.	.	6.7	0.2	3.2	9.8	6.2	0.8	5.6	1.8
2000	1.1	2.5	5.9	5.8	0.4	.	2.4	8.2	10.3	0.9	.	.	7.5	0.3	0.2	2.4	.	0.4	4.0	0.2
2001	2.1	12.8	4.3	7.9	0.8	.	12.1	5.8	12.0	1.9	.	.	13.1	0.0	6.0	11.7	3.5	.	4.8	5.4
2002	1.0	4.8	1.9	3.2	2.3	.	2.7	3.7	5.8	2.1	.	.	8.0	0.0	0.2	2.9	.	.	.	.
2003	1.9	2.0	7.3	4.6	1.8	.	12.2	16.0	9.7	2.2	.	.	10.7	1.3	1.5	4.9	7.2	1.6	.	3.5
2004	0.4	1.1	0.0	1.6	1.0	.	9.0	3.9	6.4	0.8	.	.	2.7	0.0	0.5	1.5	0.8	0.3	.	0.0

Table 3.5. Densities of age-2 and older parr by site and year in the Tobique River, NB, estimated by electrofishing from 1979 to 2004.

	Site Number																			
Year	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20
1979	1.9	5.6	.	12.5	2.0	1.1	1.5	.	7.2	.	.	.	7.3	.	.	.	.	.	.	.
1980	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1981	0.8	4.1	2.2	5.0	0.0	3.7				5.1	2.9	0.0	2.9	0.0			.	.	.	.
1982	0.4	0.3	3.3	1.2	0.0	0.3	0.0	0.0	1.6	1.8	0.0	0.0	1.4	0.0	0.0		.	.	.	.
1983	0.3	0.4	7.5	0.0	0.9	1.0	0.4	0.6	0.3	0.6	0.0	0.6	4.5	0.0	0.0		.	.	.	.
1984	0.4	1.1	0.6	2.8	1.3	0.0		0.3	1.7	0.4	0.0	0.0	2.3	0.0	0.0		.	.	.	.
1985	0.0	0.2	2.1	2.4	0.8	0.3	3.0		0.4	1.8	0.0	0.0	2.7	0.9	2.5	4.5	.	.	.	.
1986	0.0	1.2	2.2	1.3	2.2	2.1	5.0		1.1	2.2	0.2	0.0	2.4	1.1	0.0	33.8	.	.	.	.
1987						.					.	.					.	.	.	.
1988						.	0.2		1.4	3.2	0.2	.		0.0			.	.	.	.
1989						.	0.0		2.0	3.0	0.0	.		0.0			.	.	.	.
1990						.					.	.					.	.	.	.
1991						.					.	.					.	.	.	.
1992	0.2	0.1	0.4			.	0.2		2.4	6.9	0.2	.		0.1			.	.	.	.
1993		0.0	2.9			.	0.0		11.0	0.2	0.1	.		0.2			0.0	0.0	.	0.0
1994			1.5			.	0.0		0.1	0.9	0.1	.		0.2			.	0.0	0.0	0.0
1995			5.8	4.1		.	3.3		0.0	3.8	0.0	.		0.0			.	0.0	0.0	0.0
1996	0.0	2.5	1.5	1.8	0.2	.	0.2	4.0	2.5	0.6	0.2	0.2	3.8	0.0	1.0		0.0	0.0	0.0	0.0
1997	0.0	0.2	0.9	1.6	0.4	.	1.8	4.3	1.6	3.0	.	.	2.6	0.0	0.2		0.0	0.0	0.0	0.0
1998	0.1	1.3	0.4	0.7	1.2	.	1.1	0.2	3.0	1.7	.	.	0.8	0.0	0.5	0.6	0.0	0.0	0.0	0.0
1999	0.0	1.2	1.2	0.7	1.7	.	0.6	2.5	2.4	4.8	.	.	2.6	0.0	0.5	0.3	0.0	0.0	0.0	0.0
2000	0.0	0.4	0.1	0.4	0.1	.	0.4	2.8	1.4	0.2	.	.	1.5	0.0	0.0	0.4	.	0.0	0.0	0.0
2001	0.0	1.0	0.5	1.5	0.2	.	0.5	1.6	0.8	0.5	.	.	0.9	0.0	1.4	0.2	0.0	.	0.0	0.0
2002	0.1	0.2	0.5	0.2	0.2	.	0.6	0.0	0.6	0.9	.	.	1.4	0.0	0.0	0.5	.	.	.	.
2003	0.3	0.4	0.5	0.0	0.0	.	0.6	1.9	0.8	0.3	.	.	10.7	0.0	0.0	0.0	0.0	0.0	.	0.0
2004	0.0	0.2	0.4	2.0	1.0	.	2.0	0.5	1.1	1.1	.	.	2.7	0.0	0.0	0.8	0.0	0.0	.	0.0

Table 3.6. Comparison of 2 ways of calculating annual mean juvenile parr densities. The columns labeled “Generalized linear model” are obtained by using a generalized linear model to estimate site effects, which are then used to estimate values for sites that are not fished all years prior to calculating the mean. “N” is the number of sites electrofished each year. The numbers in brackets are standard errors of the mean (from Gibson et al. *in press*).

		Sample mean			Generalized linear model		
Year	N	Age-0	Age-1	Age-2	Age-0	Age-1	Age-2
1979	8	25.31 (8.2)	15.61 (7.06)	4.89 (1.42)	17.29 (4.3)	12.09 (2.69)	4.38 (1.87)
1981	11	71.12 (14.71)	8.13 (2.31)	2.43 (0.6)	66.54 (14.1)	8.56 (1.62)	2.64 (0.96)
1982	15	20.4 (7.48)	9.37 (2.29)	0.69 (0.25)	17.9 (3.25)	9.35 (1.52)	0.68 (0.21)
1983	15	10.03 (3.4)	3.92 (1.5)	1.13 (0.54)	8.8 (1.6)	3.91 (0.63)	1.12 (0.35)
1984	14	13.05 (8.14)	2.54 (0.98)	0.77 (0.25)	12.72 (2.39)	2.57 (0.43)	0.76 (0.24)
1985	15	34.69 (12.91)	3.98 (1.07)	1.44 (0.36)	30.85 (5.6)	3.88 (0.63)	1.2 (0.37)
1986	15	15.24 (5.61)	10.64 (2.44)	3.65 (2.18)	13.56 (2.46)	10.39 (1.69)	3.05 (0.95)
1988	5	54.72 (19.01)	4.08 (1.08)	1 (0.6)	38.65 (12.15)	4.45 (1.25)	1.09 (0.59)
1989	5	12.42 (7.69)	8 (2.78)	1 (0.63)	8.77 (2.76)	8.72 (2.45)	1.09 (0.59)
1992	8	20.74 (8.11)	5.38 (2.38)	1.31 (0.84)	16.43 (4.08)	5.93 (1.32)	1.46 (0.62)
1993	10	24.7 (8.08)	6.23 (2.09)	1.44 (1.1)	23.75 (5.28)	7.08 (1.41)	2.06 (0.79)
1994	9	10.82 (7.33)	3.98 (1.34)	0.31 (0.18)	10.72 (2.51)	4.37 (0.92)	0.46 (0.18)
1995	10	31.76 (14.61)	6.26 (2.39)	1.7 (0.72)	29.5 (6.56)	5.86 (1.17)	2.18 (0.83)
1996	18	6.4 (2.43)	4.37 (0.71)	1.03 (0.32)	6.88 (1.14)	4.67 (0.69)	1.27 (0.36)
1997	16	14.78 (3.86)	4.5 (0.68)	1.04 (0.33)	15.61 (2.74)	4.36 (0.69)	1.17 (0.35)
1998	17	10.32 (4.43)	8.11 (1.2)	0.68 (0.19)	11.11 (1.89)	7.55 (1.15)	0.61 (0.18)
1999	17	8.43 (2.89)	5.38 (0.94)	1.09 (0.32)	9.08 (1.55)	5.01 (0.76)	0.97 (0.28)
2000	16	14.34 (3.99)	3.28 (0.82)	0.48 (0.2)	15.6 (2.74)	3.01 (0.47)	0.4 (0.12)
2001	16	8.03 (3.99)	6.51 (1.13)	0.57 (0.14)	8.29 (1.46)	5.9 (0.93)	0.48 (0.14)
2002	13	6.14 (2.84)	2.96 (0.62)	0.41 (0.11)	5.91 (1.15)	2.56 (0.45)	0.28 (0.09)
2003	16	0.64 (0.37)	5.52 (1.14)	0.97 (0.66)	0.69 (0.12)	5.13 (0.81)	0.81 (0.25)
2004	16	9.3 (3.92)	1.87 (0.63)	0.73 (0.21)	10.01 (1.76)	1.74 (0.27)	0.61 (0.19)

Table 3.7. Estimated number of wild-origin smolt emigrating from the Tobique River, NB, from 2001 to 2005 (from Gibson et al. *in press*).

Year	Pre-smolt (enumerated previous fall)	Smolt (enumerated during spring)	Total
2001	3,788[a]	2,240	6,028
2002	10,400	6,150	16,550
2003	4,684[a]	2,770	7,454
2004	7,965[a]	4,710	12,675
2005	5,750[a]	3,400	9,150

[a] Estimated from the ratio of the fall pre-smolts in 2001 to the spring smolts in 2002 (Jones et al. 2004).

Table 3.8. Age composition of smolts sampled during the spring on the Tobique River, NB, from 2000 to 2005.

		Number Sampled			
Year	Site	age-1	age-2	age-3	age-4
	Main Stem near Three Brooks - Rotary Screw Trap				
2001		0	18	16	0
2002		0	66	21	0
2003		0	8	15	1
2004		0	193	57	1
2005		0	27	20	0
	Headpond - Trapnet				
2000		0	1	2	0
2001		0	0	4	0
	Main Stem near Odell - Rotary Screw Trap				
2000		0	8	5	0
	Wapske River - Fykenet				
2004		0	0	0	0
	Main Stem near Plaster Rock - Rotary Screw Trap				
2005		0	29	15	0
	Combined - all counting devices				
2000		0	9	7	0
2001		0	18	20	0
2002		0	66	21	0
2003		0	8	15	1
2004		0	195	60	1
2005		0	56	35	0

Table 3.9. Age composition of pre-smolts sampled during the fall on the Tobique River, NB, from 2000 to 2004.

Year	Site	Number		
		age-1	age-2	age-3
	Main Stem near Three Brooks			
2000		58	44	0
2001		24	8	0
2002		119	57	0
2003		78	35	0
2004		31	14	0
	Main Stem near Plaster Rock			
2000		43	26	0
2001		167	151	4
	Main Stem near Nictau			
2000		23	29	0
2001	no age available			
2002	no age available			
2003		15	6	0
2004		47	52	0
	Combined			
2000		124	99	0
2001		191	159	4
2002		119	57	0
2003		93	41	0
2004		78	66	0

Table 3.10. Parameter estimates for the freshwater production model for Atlantic salmon in the Tobique River, NB.

Parameter	Estimate	Standard Error
Coefficients:		
egg deposition: 1989	1.99E+07	9.08E+06
1990	2.00E+07	8.61E+06
1991	1.01E+07	2.95E+06
1992	1.58E+07	4.47E+06
1993	8.32E+06	2.24E+06
1994	1.35E+07	3.92E+06
1995	5.05E+06	1.34E+06
1996	1.08E+07	2.93E+06
1997	6.21E+06	1.58E+06
1998	3.43E+06	7.91E+05
1999	6.74E+06	1.74E+06
2000	2.62E+06	5.88E+05
2001	3.52E+06	7.42E+05
2002	1.13E+06	2.87E+05
2003	4.41E+06	1.32E+06
2004	1.83E+06	9.15E+05
H	2.17E+04	8.82E+03
M^{egg}	9.63E-01	1.64E-02
α	9.30E-01	2.85E-01
R_{asy}	9.31E+00	2.39E+00
M^{parr}	7.47E-01	5.64E-02
S_2	3.73E-01	6.71E-02
S_3	9.73E-01	2.73E-02

Table 3.11. Estimates of the number of smolt emigrating from the Nashwaak River, NB, and the smolt-to-adult (1SW and 2SW salmon) return rates for those smolt year classes (from Gibson et al. *in press*).

Smolt Year	Smolt Estimate	Return Rate		
		1SW	2SW	Total
1998	22,750	0.0291	0.0067	0.0357
1999	28,500	0.0179	0.0084	0.0262
2000	15,800	0.0153	0.0028	0.0182
2001	11,000	0.0311	0.0090	0.0401
2002	15,000	0.0191	0.0126	0.0317
2003	9,000	0.0638	0.0158	0.0796
2004	13,600	0.0513		
2005	5,200			

Table 3.12. Previous spawning history of wild Tobique River salmon from 1989 to 2004.

	Number of Previous Spawnings				
Year	0	1	2	3	Total
1989	7,196	110			7,306
1990	6,221	124	12		6,358
1991	6,218	106	12		6,336
1992	5,705	89			5,794
1993	3,476	46			3,522
1994	2,361	36			2,397
1995	3,114	29			3,143
1996	2,442	31			2,473
1997	950	61			1,011
1998	448	26	5		480
1999	777	15			792
2000	1,304	31			1,334
2001	755	7			762
2002	479	7			486
2003	346	9			355
2004	557	3			560
Total	42,350	730	30		43,109

Table 3.13. Comparison of the Tobique River freshwater production and survival estimates with those from the Big Salmon River (from Gibson and Bryan, in prep.).

	Parameter Value	
Parameter	Tobique	Big Salmon River
Egg to Fry Survival	0.962	0.967
Beverton-Holt α (age-1)	0.929	0.691
Beverton-Holt R_{asy} (age-1)	9.31	22.49
Mortality of age 1+ parr	0.747	0.503
Prob. smolting (age 2)	0.373	0.397
Prob. smolting (age 3)	0.973	0.924
Maximum number of smolts per egg	0.0046	0.0077
Smolt R_{asy} (number per 100m^2)[1]	1.24	7.55

[1] "effective" habitat units used for calculation, based on the electrofishing catchabilities

Table 4.1. Estimates of the number of smolt emigrating from the LaHave River, NS, and the 1-sea-winter and 2-sea-winter return rates for those smolt years.

Smolt year	Number of smolt	1SW return rate	2SW return rate
1996	20,510	1.47	0.26
1997	16,550	4.33	0.53
1998	15,600	2.04	0.43
1999	10,420	4.82	0.97
2000	16,300	1.16	0.23
2001	15,700	2.7	0.63
2002	11,860	1.95	0.56
2003	14,034	1.75	0.24
2004	21,613	1.09	NA

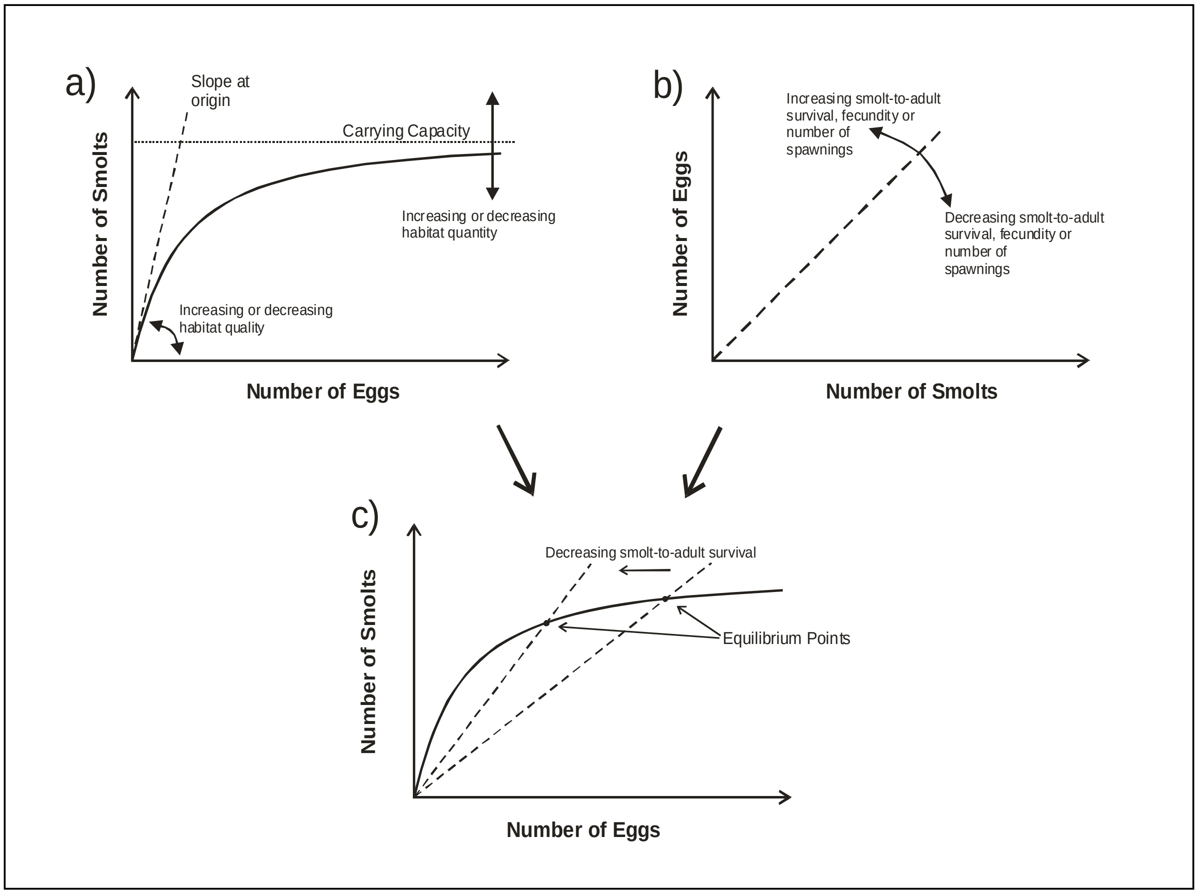

Figure 2.1. An equilibrium model linking habitat quality and quantity to fish population dynamics. A Beverton-Holt model (a) is used to model the density-dependent relationship for survival from eggs to smolt. The slope at the origin of this model, which is the maximum number of smolts produced per egg in the absence of density dependent effects, changes as habitat quality changes, whereas changes in the amount of habitat changes the carrying capacity. The number of eggs produced per smolt (b) throughout its life, changes with smolt-to-adult survival, fecundity, age-at-maturity, or the number of times a fish spawns throughout its life. The population equilibrium (c) occurs at the population size where the production of smolts by eggs is in balance with the production of eggs by smolts throughout their lives, and is the size at which the population will stabilize if all rates and the carrying capacity remain unchanged. The population equilibrium changes as the vital rates change and can be used to assess how a population is expected to change in response to human activities.

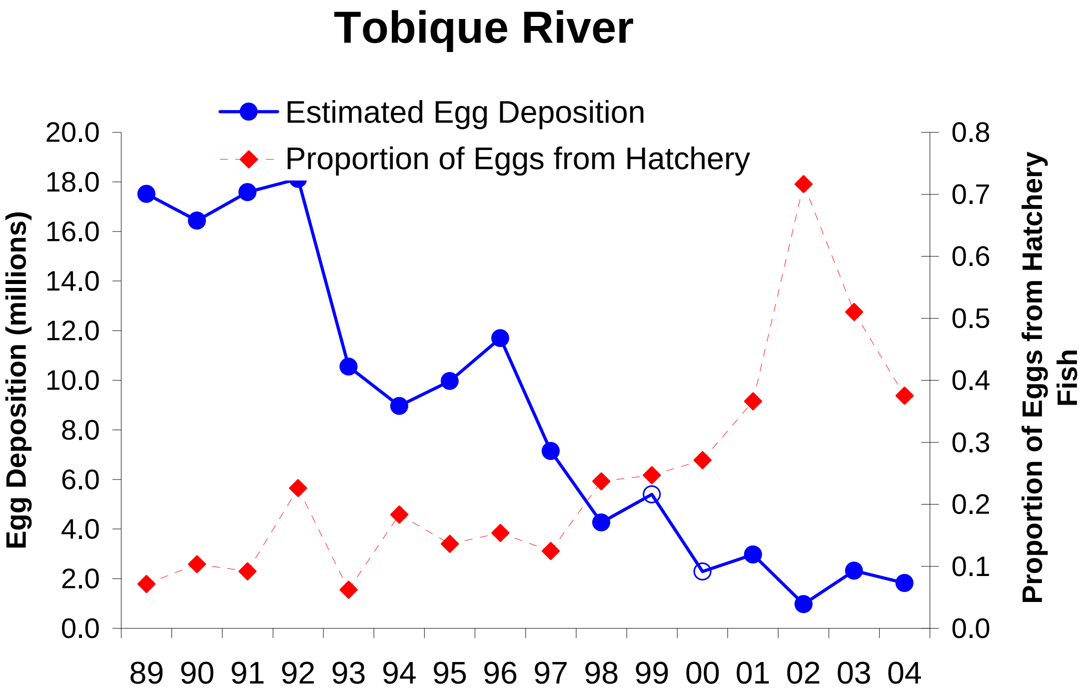

Figure 3.1. Egg deposition and the proportion of eggs from fish of hatchery origin in the Tobique River, NB, from 1989 to 2004 (from Gibson et al. in press).

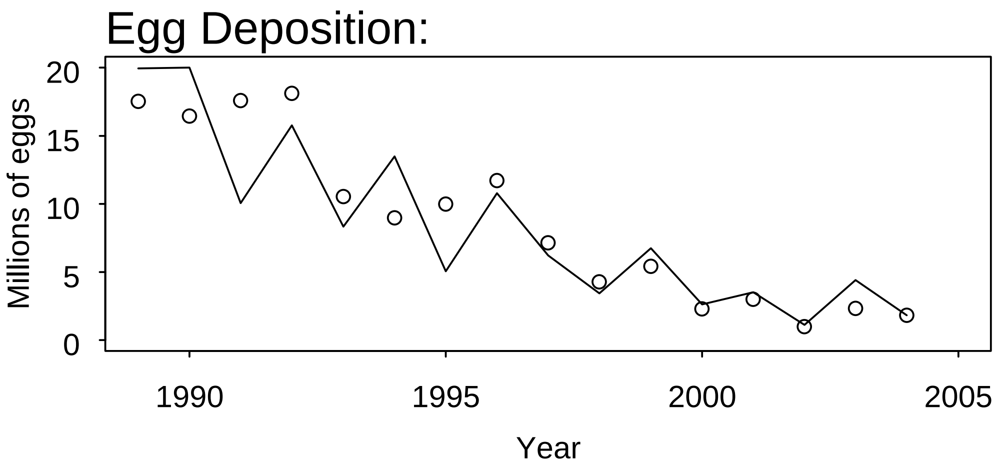

Figure 3.2. Egg deposition in the Tobique River, NB, from 1989 to 2004. The points are the observed annual egg depositions, while the lines are predictions from the freshwater production model (from Gibson et al. in press).

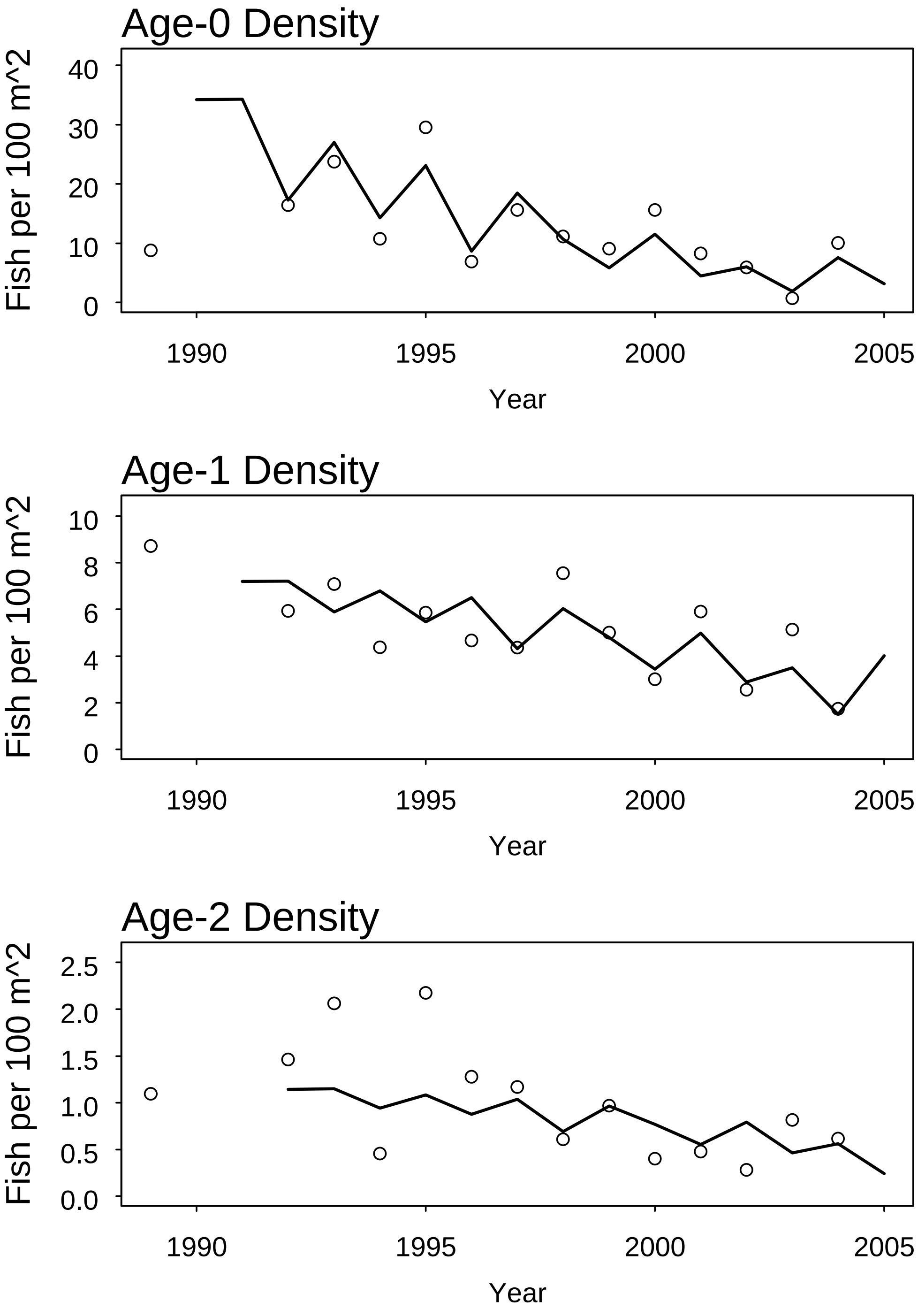

Figure 3.3. Mean densities of juvenile Atlantic salmon in the Tobique River, NB, from 1988 to 2004. The points are the observed densities determined by electrofishing. The lines are the predicted densities from the freshwater production model (from Gibson et al. in press).

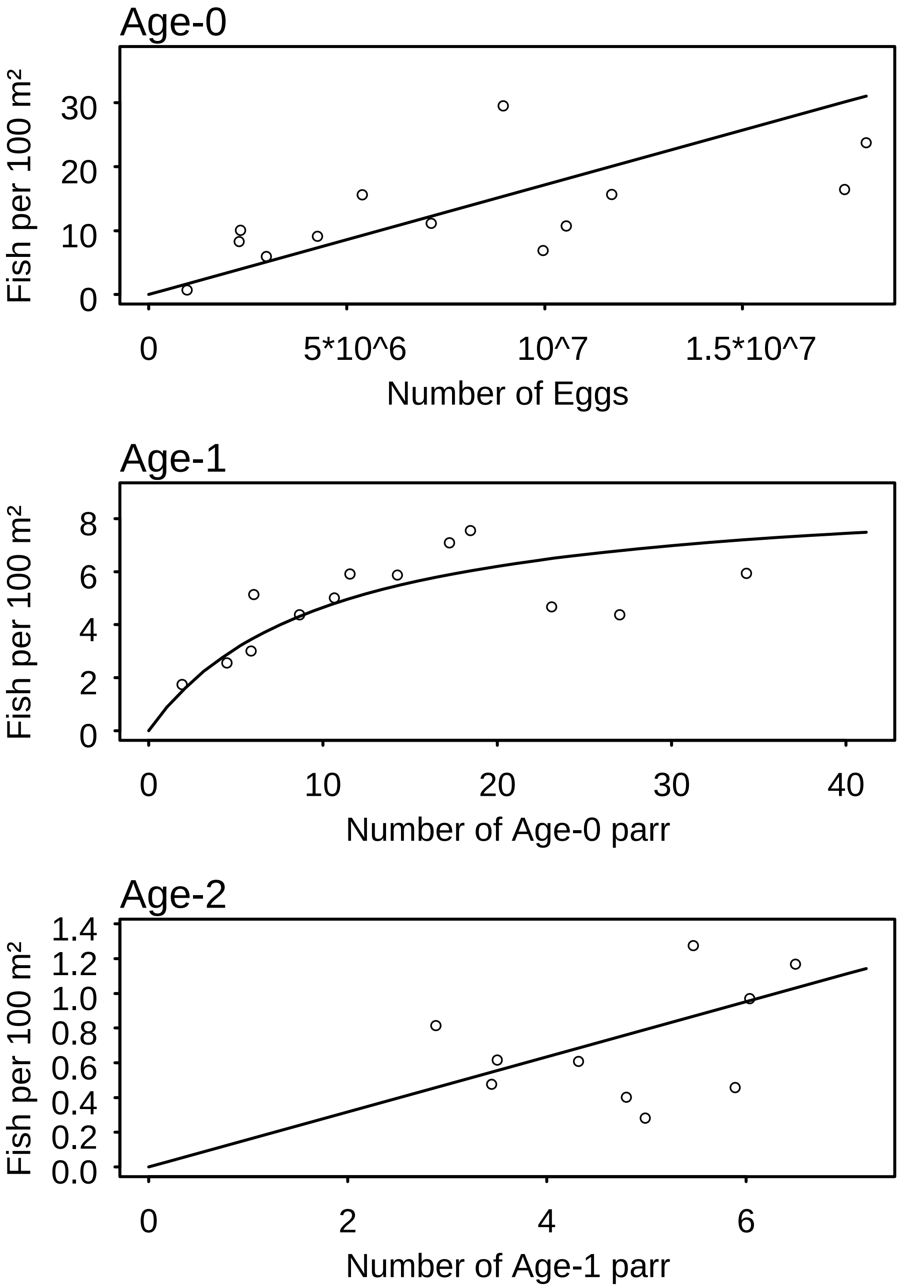

Figure 3.4. Scatterplots comparing the abundance of salmon within a cohort at different ages for the early life stages of Atlantic salmon in the Tobique River, NB. Each point represents the density of a single cohort at 2 ages. The lines represent the relationships estimated with the freshwater production model, assumed density independent for the eggs to age-0 and age-1 to age-2 transitions and density dependent for the transition between age-0 and age-1 (from Gibson et al. in press).

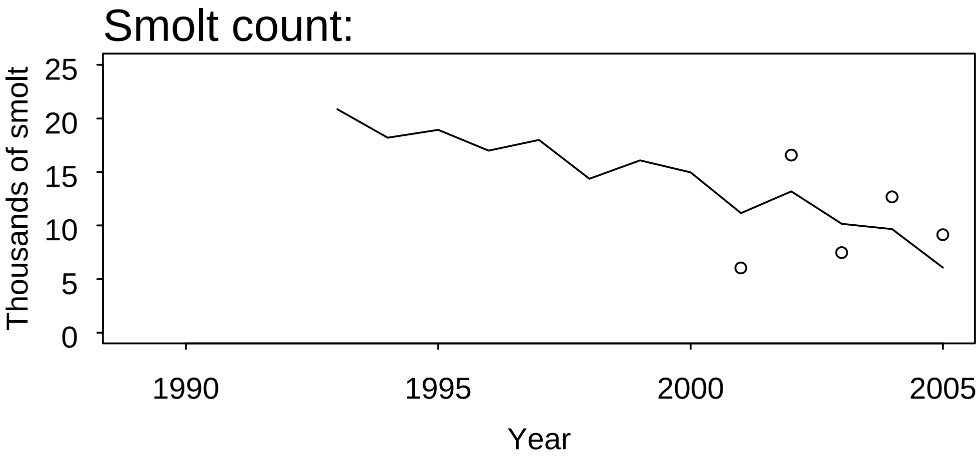

Figure 3.5. Number of smolts emigrating from the Tobique River, NB. The points are the estimates based on in-river counts, while the lines are predictions from the freshwater production model (from Gibson et al. in press).

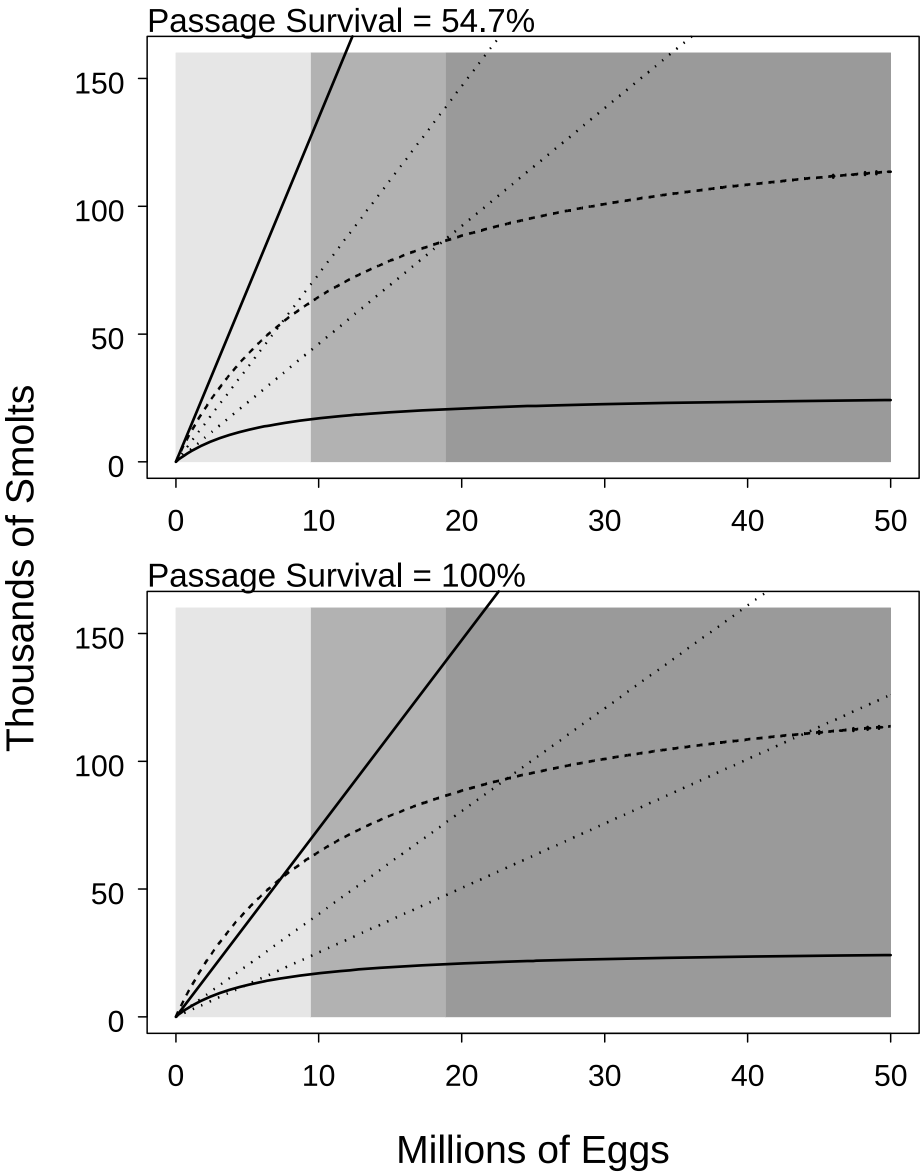

Figure 3.6. Analysis of the effects of alleviating threats to the Tobique River salmon population. In both panels, the curved solid line is the production curve obtained from the freshwater production model, and the curved dashed line is the freshwater production curve obtained if the asymptotic recruitment level is doubled to 18.6 age-1 parr per 100 m^2 and survival of age-1 and older parr is doubled to 49%. Three replacement lines are shown: the slope of the solid line is calculated using the average return rates from Nashwaak River, the middle line is calculated using the maximum observed rates, and the left dashed line represents a hypothetical scenario of 8% and 3% return rates for 1SW and 2SW salmon, respectively. The dynamics are shown for 2 fish passage scenarios: fish passage mortality of 45% (status quo) and fish passage mortality reduced to zero. Dark shading indicates egg depositions above the conservation egg requirement: the medium shading is between 50% and 100% the egg requirement, and the light shading is below the requirement (from Gibson et al. in press).

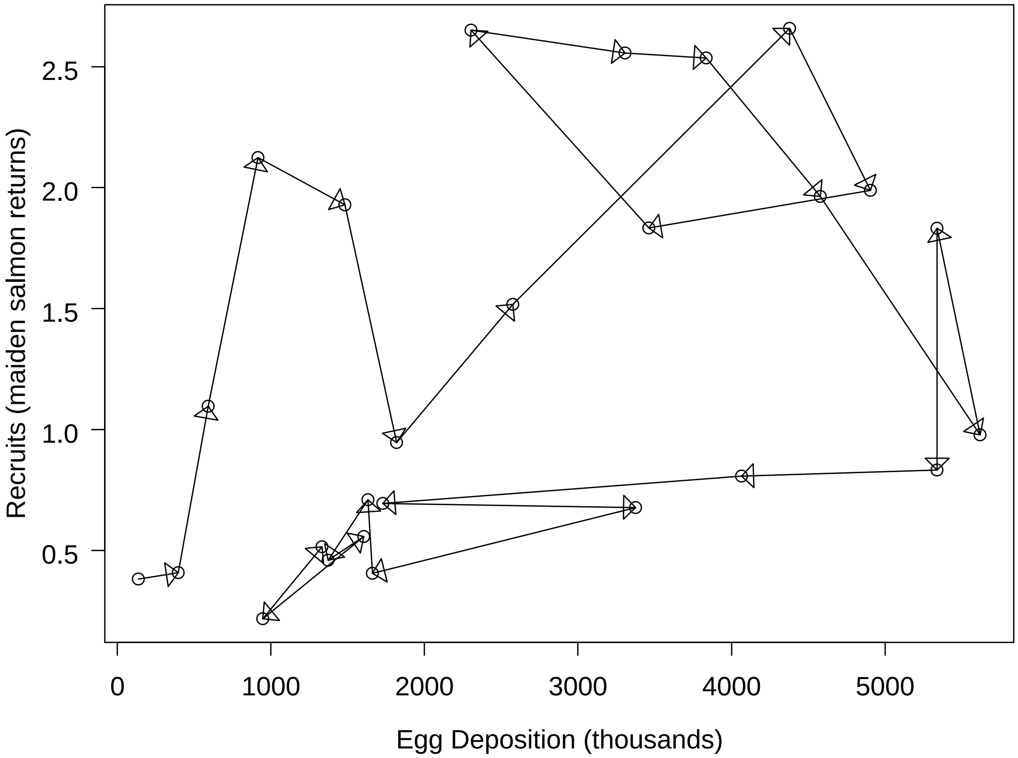

Figure 4.1. Spawner (egg deposition) – recruit data for the Atlantic salmon population above Morgan Falls in the LaHave River, NS, from 1973 to 1998 (egg deposition year).

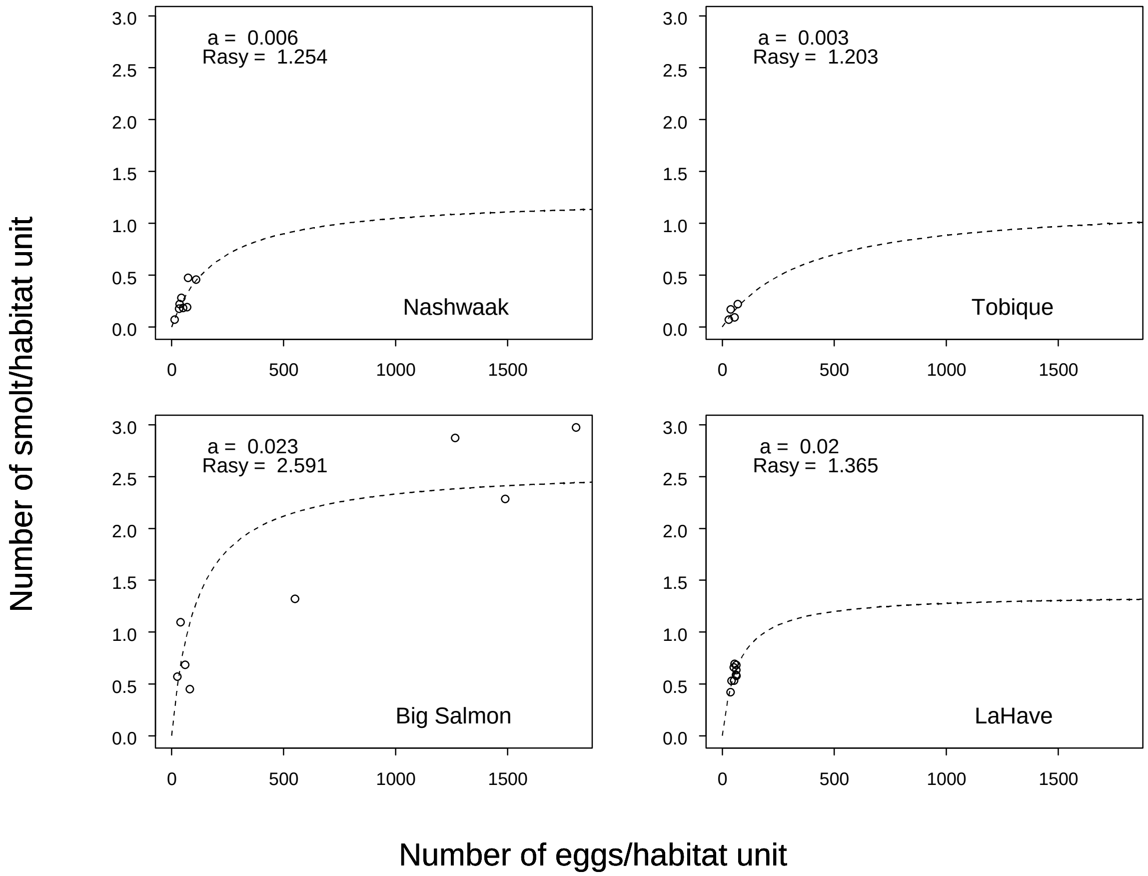

Figure 4.2. Relationship between egg deposition and smolt production for 4 Atlantic salmon populations in the Maritime Provinces. Data are standardized by the amount of salmon habitat in each watershed. The slope at the origin of the relationship, "a", is the maximum number of smolts produced per egg in the absence of density dependence. The carrying capacity, "R_{asy}", is expressed as the number of smolt per habitat unit (1 unit = 100 m^2 of habitat).

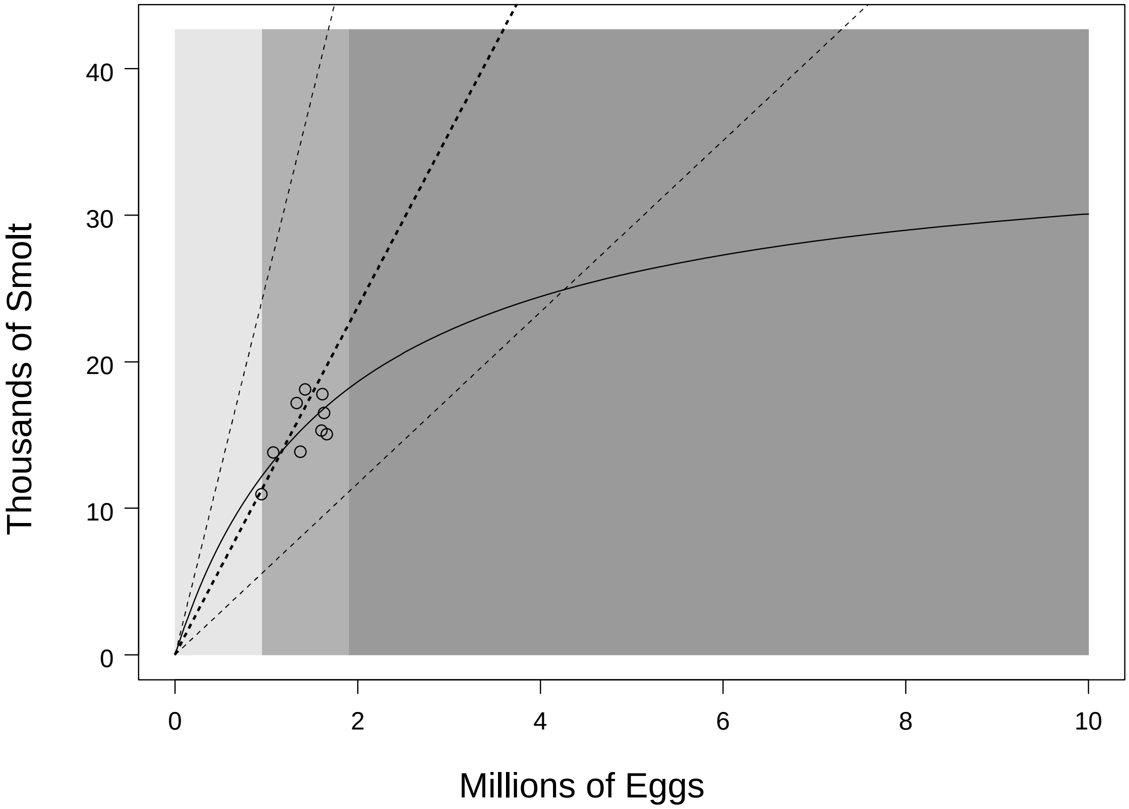

Figure 4.3. Dynamics of the salmon population in the LaHave River, NS, above Morgan Falls. The points are the observed egg depositions and smolt production for the 1994 to 2001 egg cohort years. The solid line is a Beverton Holt model obtained by fitting to this spawner-recruit data. The dashed lines show the replacement lines calculated using the minimum, average, and maximum smolt to adult return rates observed for this population between 1996 and 2004. 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.

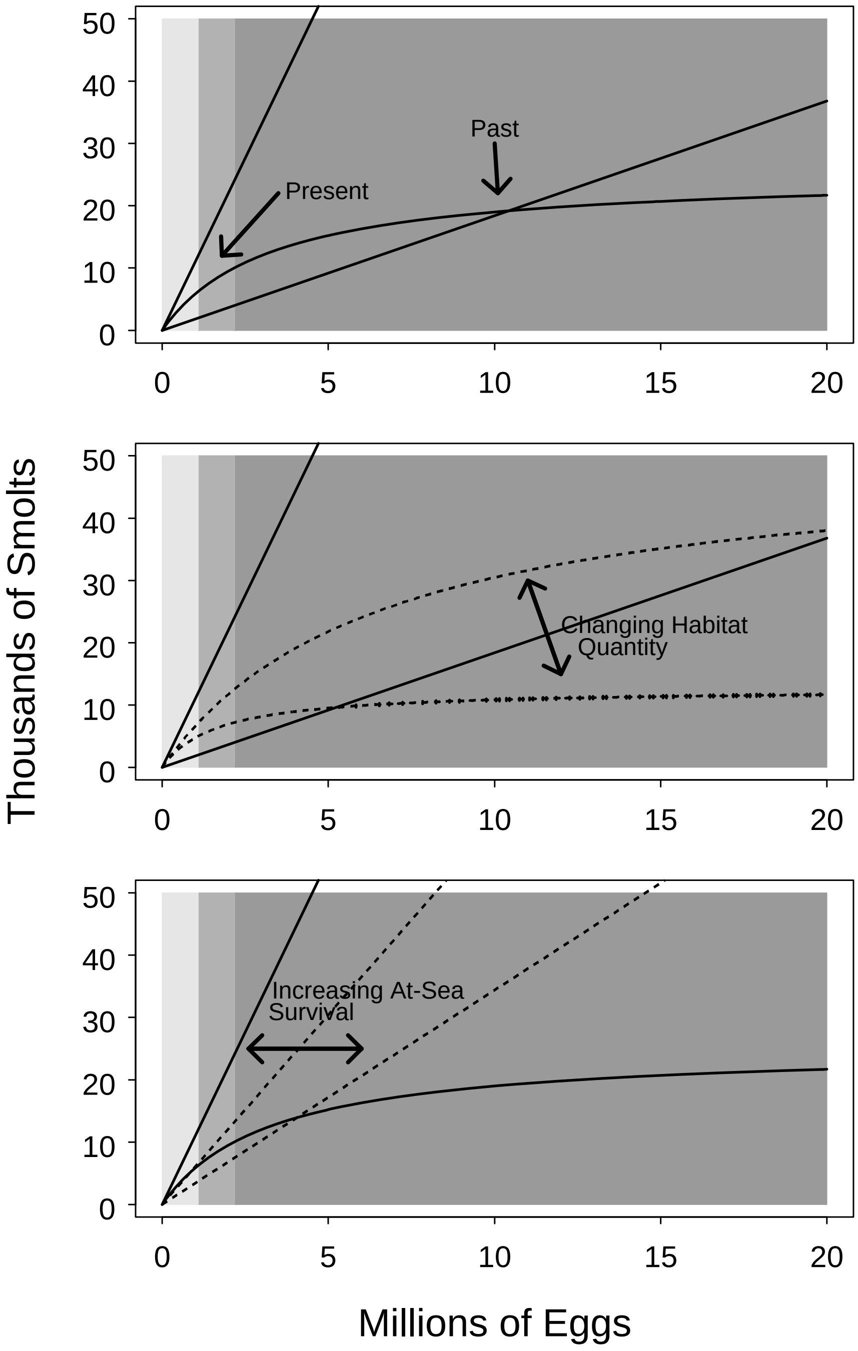

Figure 5.1. Equilibrium analysis for salmon of the Big Salmon River, NB. Top panel: the change in equilibrium population size resulting from a decrease in at-sea survival between 2 time periods; the past (1967-1971) and present (2001-2004). Middle panel: the effect of doubling or halving the amount of freshwater habitat (dashed lines) on equilibrium population size given replacement lines calculated using the past (right solid line) and present (left solid line) at-sea survival rates. Bottom panel: the effect of increasing return rates to 0.5% for 2SW salmon and 2% for 1SW salmon (middle dashed line) or 1.0% for 2SW and 4% for 1SW salmon (left dashed line). 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.

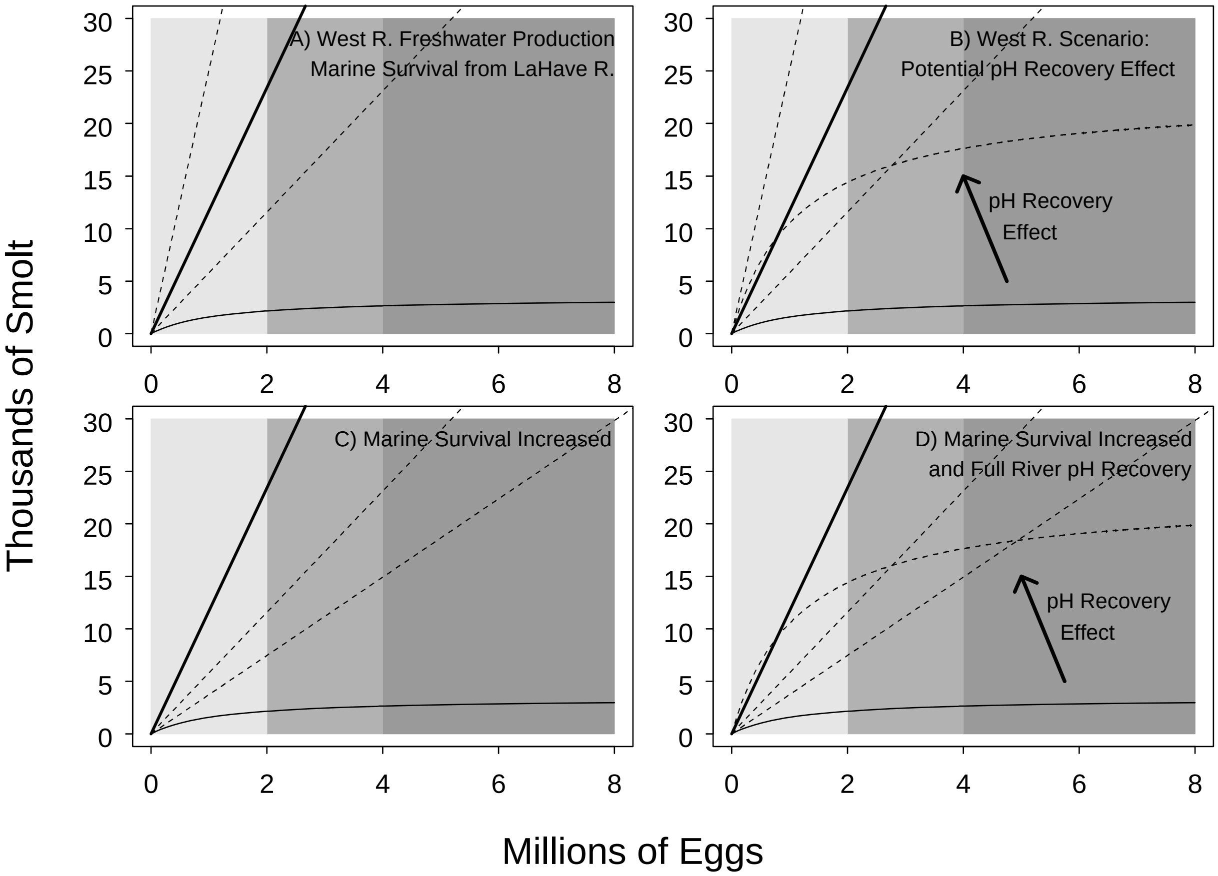

Figure 6.1. Equilibrium analysis of the recovery potential of salmon in West River (Sheet Harbour, NS). The upper left panel shows the present dynamic in which populations are not viable as a result of low marine survival and reduced freshwater production due to acidification. The slopes of the replacement lines are calculated using the mean, minimum, and maximum return rates observed for LaHave River salmon from 1996 to 2004. The upper right panel shows the expected change in freshwater production, if the acidification problem was addressed in the entire river. The lower left panel shows the dynamics if freshwater production remains unchanged and at-sea survival rates are the mean and maximum return rates from the Lahave River, NS, together with a hypothesized return rate increase to 6% for 1SW and 2% for 2SW salmon. The lower right panel shows a scenario with a combined increase in freshwater production and marine survival, in which the conservation egg requirement is reached. 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.