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Identification and exploration of some methods for designation of critical habitat for survival and recovery of inner Bay of Fundy Atlantic salmon (*Salmo salar*).

Identification et exploration de quelques stratégies de désignation de parcelles d'habitat critiques pour la survie et le rétablissement du saumon atlantique (*Salmo salar*) de l'arrière-baie de Fundy.

Peter G. Amiro, J. Gibson and K. Drinkwater

Science Branch, Bedford Institute of Oceanography
Department of Fisheries and Oceans
PO Box 1006, Dartmouth, NS
B4Y 4A2

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Abstract

In this document, we examine the implications of survival and recovery strategies on the designation of critical habitat for populations of Atlantic salmon in the inner Bay of Fundy (iBoF). We review the literature about habitat requirements for Atlantic salmon by life stage, and describe an approach for estimating the productive capacity of freshwater habitat using remote-sensed data and historical distributions. Complications to the designation of critical habitat introduced by uncertainties in life-history strategies, and recovery targets are discussed. Within the marine environment, we use sea surface temperature (SST) as a measure of habitat preference, and use mean SST to delineate preferential areas within the Bay of Fundy and Gulf of Maine on a month by month basis. Strategies to attain survival through supportive breeding and rearing to maturity have different habitat requirements from those based on recovery. Recovery strategies require designation of critical marine habitat as well as freshwater habitat. To date, population and physical habitat inventories have delineated 9 $\times 10^6$ m^2 of productive salmon habitat within 22 rivers within the iBoF. The marine habitat for iBoF salmon is thought to be more localized than for other Atlantic salmon populations. Based on historic tagging, thermal requirements of salmon at sea, and sea surface temperatures in the Bay of Fundy and Gulf of Maine, critical marine habitat for recovery of iBoF salmon is proposed.

Résumé

Nous examinons les répercussions de stratégies de survie et de rétablissement sur la désignation de parcelles d'habitat critiques pour les populations de saumon atlantique de l'arrière-baie de Fundy. Nous passons en revue des études publiées sur les exigences en matière d'habitat des divers stades du cycle biologique de l'espèce, puis nous décrivons une méthode d'estimation de la capacité de production de l'habitat d'eau douce reposant sur des données de télédétection et de répartition historique. Nous faisons aussi état des complications que pose la désignation de parcelles d'habitat critiques résultant des incertitudes qui entourent les stratégies reposant sur les stades du cycle biologique, puis nous établissons des cibles de rétablissement. Au plan du milieu marin, nous utilisons la température de la surface de la mer (SST) comme mesure de la préférence en matière d'habitat et la SST moyenne pour délimiter les endroits privilégiés par l'espèce dans la baie de Fundy et le golfe du Maine d'un mois à l'autre. Les stratégies visant à assurer la survie de ce saumon par le biais de la sélection et de l'élevage en captivité jusqu'à la maturité reposent sur des exigences en matière d'habitat différentes de celles visant le rétablissement. Les stratégies de rétablissement requièrent la désignation de parcelles d'habitat marin critiques ainsi que de parcelles d'habitat en eau douce. Jusqu'à maintenant, les relevés d'effectifs et les inventaires de parcelles d'habitat physique ont permis de délimiter des parcelles d’habitat productives en saumon de 9 x 10^6 m^2 dans 22 cours d’eau de l’arrière-baie de Fundy. On croit que les parcelles d’habitat marin de ce saumon sont plus localisées que cela n’est le cas pour d’autres populations de saumon atlantique. D’après des données d’étiquetage, les exigences thermiques du saumon en mer et les SST dans la baie de Fundy et le golfe du Maine, nous proposons des parcelles d’habitat marin critiques pour le rétablissement du saumon atlantique de l’arrière-baie de Fundy.

Introduction

Atlantic salmon (*Salmo salar* L.*)* is a species of fish that is endemic to the northern temperate hemisphere (MacCrimmon and Gots 1979). Domestic strains are now cultured in many temperate climates worldwide (Gross 1998). In the wild, salmon most often follow a life history that utilizes both marine and freshwater environments. Spawning and rearing occurs in fresh water and the majority of growth to maturity takes place in the ocean environment.

An assemblage of salmon found in rivers northeast of the Saint John River in New Brunswick and northeast of the Annapolis River in Nova Scotia (Figure 1) has been termed “inner Bay of Fundy” (iBoF) salmon (Perley 1852). Almost all salmon within these rivers have similar life history traits that differ from those of the outer Bay of Fundy and the Atlantic coast. Inner Bay of Fundy salmon demonstrate more localized migration, earlier age at maturity and high survival between annual spawning events. Also, iBoF salmon appear to be dependent on repeat spawning for population stability more frequently than salmon in other areas (Amiro 1987). Based on an analysis of phylogenetically informative mitochondrial DNA (mtDNA) variation in Atlantic salmon stocks in the southern sector of the species eastern North American range, Verspoor et al*.* (2002) suggested that two distinct, evolutionarily defined populations exist within the inner Bay of Fundy.

Wild anadromous Atlantic salmon of the inner Bay of Fundy (iBoF) have declined 90% or more in abundance since 1989. In May, 2001 the Committee On the Status of Endangered Wildlife In Canada (COSEWIC) listed the entire iBoF salmon stock complex as *Endangered*. In accordance with Species at Risk legislation for Canada, the iBoF Salmon Advisory Group was designated as the “iBoF Salmon Recovery Team”. Among the requirements for the “Recovery Strategy” is an evaluation of a critical habitat designation for survival or recovery of the stock complex.

In this document, we examine the application of some methods that could be used to identify critical habitat requirements for Atlantic salmon by life stage, and outline the implications of potential differences between survival and/or recovery strategies on critical habitat designation for iBoF Atlantic salmon. The complications to the designation of critical habitat introduced by uncertainties in alternative life-history strategies, meta-population structure and variable recovery targets are discussed.

Methods

Reference tables listing North American Atlantic salmon habitats by life stage were assembled from published literature. Descriptions of the methods and results that defined and identified habitat for life stages of Atlantic salmon in freshwater and marine environments were sought. The literature review for the marine phase was restricted to iBoF salmon populations because tag recoveries for iBoF salmon come primarily from the Bay of Fundy and Gulf of Maine, suggesting a marine distribution that differs from other North American populations. Three spatial scales were used to classify the information. Information for habitat descriptors at the millimeter to centimeter scale were termed “micro-“, while information on the centimeter to 10’s of meters scale were termed “meso-“. Descriptors on larger spatial scales that could be measured using remote sensed data were termed “macro-“.

Freshwater production

We estimated juvenile salmon production for 22 inner Bay of Fundy rivers using the approach of Amiro (1993) and Korman et al. (1994) to link habitat quality to salmon production. Our objective was to identify and rank (in terms of production) salmon habitat within a watershed on a reach-by-reach basis, and to use these results to estimate the productive capacity among watersheds. In so doing, the areas with the greatest potential contribution to the salmon production within the iBoF were identified on the meso- and macro- scales. Three steps were required for this process:

1. Select variable(s) that is indicative of habitat quality and transferable across scales i.e. a variable needs to be measurable at both the meso- (using in-situ methods) and macro- (using remote sensing methods) scale.

2. Link to salmon production via:
    I. selection of production indicator and target
    II. selection of a model linking habitat to production
    III. parameterize the model using field-based observations and re-scale to a target

3. Determine both the quantity and quality of habitat available within target watersheds and estimate productive capacities. Quantity and quality of habitats are determined via remote sensing and once the productive capacity of habitat is estimated on the meso- scale, estimation of productive capacity on the macro-, or watershed scale is accomplished by summation.

1. Selection of a variable.

Amiro (1993) and Korman et al. (1994) used stream gradient as an indicator of habitat quality. This variable has the advantage that it can be measured in situ using standard survey methods and can also be measured from the ortho-photo maps (methods described Amiro 1993). Amiro (1993) examined the relationship between stream gradient and parr density for three rivers (including one iBoF river) and found a model including year, distance from the mouth of the river, and gradient explained 32% to 49% of the variation in parr density observed among stream reaches in these rivers.

Amiro (1993) validated the use of map-based gradient measurements by comparing area-weighted percent grade, measured *in situ,* with percent grade measured between 0.5 m contours on 1: 10,000 ortho-photo maps, and found that the following correction was required for map-based measurements of gradient to be comparable with field measurements:

Equation 1: Stream gradient = 1.201 + 0.505*Ln(Map Gradient).

2. Selection of a production indicator and target.

Following the approach of Korman et al. (1994) we used smolt production as the production criterion. Age at smoltification is partially a function of parr length attained during the previous fall (Elson 1967), and length-at-age is a function of parr density (see below). We selected a target mean parr density that would allow age-1 parr growth sufficient to attain 83% age-two smolts across gradient categories. Target densities resulting in other smoltification rates could also be selected and would result in a re-scaling of the production estimates but would not change the relative ranking of habitat.

When a length of 10 cm (age-1 parr) is reached by August in the pre-smolt year, smolt migration at age-2 can be expected (Elson 1957). We used data collected by electrofishing on the Stewiacke River (1984 - 1995) to determine the density that would allow about 50% of the age-1 parr to reach that criterion length by August of their second year. We modeled the relationship between the length of age-1 parr and the density as:

Equation 2: $Length_{age-1parr} = a - b * Ln(Density_{age-1+2parr})$,

where *a* and *b* are parameters estimated by linear regression.

Amiro (1993) and then Korman *et al.* (1994) examined the relationship between parr density and area weighted surface grade (*AWSG*) and found that of the models evaluated, a negative exponential model (equation 3) provided a better fit than other models that were tested, particularly at high and low gradients. Here, we used this equation to model the relationship between parr density and stream gradient as:

Equation 3: $Density = a(AWSG)^b e^{-AWSG}$.

Here, *a* and *b* are model parameters that were estimated by least squares regression after applying a log transformation to linearize the model. After fitting, the model is scaled so that the mean density over gradient categories matched the target density (in our example an average of 16.7 parr per $100m^2$ over the *AWSG* interval from 0 to 3; see results).

3. Estimation of productive capacity for 22 rivers.

We measured gradient for 22 inner Bay of Fundy rivers based on stream reaches defined between 5.0m contour intervals from ortho-photo maps. Gradient and length of each stream reach was measured from the maps. Stream widths were measured from 1:10,000 scale air photos and standardized to mean summer flows (Amiro 1993). Area was estimated for each reach based on these lengths and widths and summarized by gradient categories for each river.

The productive capacities by watershed were calculated using Equations 1 to 3 and remote sensed estimates of habitat area by gradient categories.

Marine habitat

Habitat requirements for the marine phase of iBoF salmon were defined using the sea surface temperature (SST) preference of Atlantic salmon sampled at sea as described by Reddin and Friedland (1993). Based on their analyses, we classified sea surface temperatures <1 C and > 13 C as *unfavourable*; SSTs between 1 C and 4 C and from 10 C to 13 C were as *low preference* and SSTs >4 C and <10 C as *high preference* areas.

Sea surface temperatures (SSTs) were derived from satellite observations made by the Jet Propulsion Laboratory (JPL). They produce weekly grids of multi-channel sea-surface temperatures (MCSSTs) from the daytime NOAA Advance Very High Resolution Radiometer (AVHRR) at a spatial resolution of 18 km. These were used to estimate monthly mean temperatures off eastern Canada for each of the years 1981 through 2000, and are archived at the Bedford Institute (Petrie and Mason 2000). They are considered reasonably accurate on the basis of comparisons with direct measurements (Mason et al. 1998). Within the present study we averaged these monthly means at each grid point for each available year to produce the long-term monthly means of SST. Note that the number of data points for each grid point for each month varies due to a combination of problems with the satellite sensors and weather conditions. These data were then contoured and colored to indicate different temperature ranges depending on the preference for salmon.

The area of application was selected based on the distribution of tags recaptured from tagged wild and hatchery-raised smolts of inner Bay of Fundy stock origin (Amiro and Jefferson 1996). The SST classification was therefore applied to the Bay of Fundy, Gulf of Maine and Scotian Shelf areas.

Live gene bank habitat requirements

A Live Gene Bank (LGB) has been initiated to maintain the potential for iBoF salmon recovery by preserving the genetic base thought to be representative of the population. The program consists of two components: the captive and "in-river" live gene banks. The first releases from the iBoF LGB into iBoF rivers occurred in 2001 as part of the "in-river" component of the program. Here, salmon of various ages are released into the rivers to provide exposure to the natural environment to allow natural selection to occur. A portion of these fish is then recaptured and brought back into the captive component of the program and mated according to a strategy designed to minimize inbreeding depression. In this way, salmon populations are being maintained through supportive rearing while attempting to limit the effects of domestication and selection of deleterious traits at times associated with fish culture programs. Some habitat is therefore required to support the "in-river" component of the LGB. The requirements for natural stream habitat for the on-going LGB for inner Bay of Fundy salmon are determined by the Inner Bay of Fundy Atlantic Salmon Recovery Team (Cullen (editor) DFO 2003).

Results

Freshwater phase

The North American literature review of the freshwater habitat requirements by life stage indicated that for most of the eight recognized life stage categories micro, meso and macro habitat descriptions and models have been published (Table 1). The notable exceptions were associated with the early life stages, egg, alevin and fry, and macro habitat identification. Macro identification of over-wintering habitat for parr and micro habitat for smolts was also unavailable.

The gradient, length and width of 7,345 reaches in 22 iBoF rivers were measured from ortho-photo maps and aerial photographs, resulting in the characterization of over 9,000,000m^2 of habitat. The mean summer low flow wetted areas of the 22 iBoF rivers (Table 2) ranged between 627m^2 (Diligent River) and 27,014m^2 (Stewiacke River).

The relationship between the length of age-1 parr and the density of age-1 and older parr for Stewiacke River salmon (Figure 2), shows decreasing age-1 parr length as total parr density increases. Both parameters in the regression model were statistically significant at a 95% confidence level (Table 3). Based on the fitted relationship, an average density of about 16.7 age-1 and older parr per 100 m^2 across habitat gradients from 0 to 3 ASWG would allow about 50% of the age-1 parr to attain smoltification the following spring. This proportion results in about 83% two-year and 17% three-year smolts at age-1overwinter survival rates of 0.5 to age-2 smolt, 0.4 to age-2 parr and 0.3 to age-3 smolt.

The relationship between stream gradient and parr density is shown in Figure 3. Both regression coefficients are statistically significant at a 95% confidence level

(Table 4). Calibration of the model to obtain mean densities of 16.7 parr/100m^2 between area-weighted stream gradients of 0 and 3 required rescaling by a factor of 1.11. The resulting model, used to estimate the productive capacity of each stream reach using the ortho-photo map-based measurements, is also shown in Figure 3 and has a mode of 21.5 parr per 100m^2.

The productive capacity for parr varied among watersheds by more than a factor of 35 (Table 5), partially as a result of the habitat area within rivers and partially as a result of different habitat quality between rivers (Figure 4). The Stewiacke River has the highest productive capacity as a result of its size (Figure 4). In contrast, the Big Salmon River, which is much smaller than the Stewiacke River, has a productive capacity that is nearly as high as the Stewiacke as a result of having more habitat in the preferred gradient categories (Table 5; Figure 4). Habitat quality, as indicated by the mean parr production per unit area within the watershed, varied by a factor of about three among these rivers (Figure 4).

Marine phase

The literature review of the marine habitat requirements by life stage indicated that for most of the five recognized life stage categories, micro habitat descriptions and models have been not been published for iBoF salmon (Table 6). The spatial analysis of potential marine habitat based on sea surface temperature preference indicates that habitat was limited to the outer Bay of Fundy and off the southwestern Nova Scotia coast in the August to September period (Figures 5 to 16). The habitat during this period was of low preference and warmer than the high preference category. Acceptable habitat was abundant in most other months. Distributions of iBoF post-smolt salmon can also be inferred from the distributions of tagged smolt recoveries (Appendix 1), and roughly match the temperature preference regions shown in Figures 5 to 16. An exception is the month of August when tags were returned in 1971 and 1973 from the Passamaquoddy Bay area that was coded unfavourable based on the 20-year average temperature.

Live gene bank

The Stewiacke and Big Salmon rivers are the largest contributors to the LGB program, while the Salmon River (Colchester Co.) has been selected as a recipient river. Based on habitat quality and the absence of indigenous populations, the Folly, Debert and Chiganois rivers are being used to warehouse LGB progeny. Collections of parr for grow out to mature brood stock for the LGB resulted in 11 rivers contributing to the LGB (Table 7). A requirement of the strategy for persistence of these populations through the LGB is that freshwater habitat is required to expose the populations to natural selection. Also, in order to reduce undesirable genetic consequences in the populations, alternative rivers are required to place broodstock that have reached their limit of family representation in the breeding plan. To date this has resulted in five additional rivers in the LGB program (Table 7). These rivers could potentially be deemed critical to the maintenance of iBoF salmon.

Discussion

The literature survey indicated that the habitat requirements for most life stages of Atlantic salmon have been documented but not at all spatial scales. While the literature review presented here cannot be considered complete, it does present a scientific basis for a general habitat model for anadromous Atlantic salmon over a range of spatial scales that can be used as a basis for habitat identification. This process is a necessary first step towards critical habitat designation. Much more information is available for freshwater habitat use than for marine habitat use particularly for iBoF salmon. Considering that marine survival is the most likely stage impacting the recovery of iBoF salmon, documenting and uncovering marine distribution of iBoF salmon remain high priorities for research. This information could weigh heavily in critical habitat designation.

Information about the habitat requirements of any species considered at risk is likely to increase as scientific interest focuses on that species. For the purposes of initiating a maintenance and recovery strategy for a species at risk, it seems precautionary to utilize proximate information to construct the initial designations and undergo additional scientific enquiry if there are substantial scientific gaps in that knowledge. Based on that approach, models taken from the literature (Tables 1 and 6) could be used as a starting point for critical habitat designation for iBoF Atlantic salmon. The historic observation of population distribution of iBoF Atlantic salmon at various life stages is evidence for those models of habitat use.

Under the Species at Risk Act the question of critical habitat for iBoF salmon must be evaluated with respect to survival and then recovery. A LGB program has been initiated for iBoF salmon as one method to maintain these populations. In this method a representative sample of the remaining genetic variation in the population is maintained in captive rearing facilities to mitigate this low survival period. A subset of these animals and their progeny are exposed to the natural environment allowing some natural selection during the higher survival stages (in this case the freshwater life stages). This procedure, combined with pedigree breeding, can reduce the rate of domestication compared to full captive rearing and breeding or extinction if non-intervention were chosen. In the case of the iBoF salmon, rearing to maturity in captivity mitigates marine survival and juvenile fish are grown (warehoused) in suitable freshwater habitat for reselection to the captive rearing facility. With respect to survival, it is clear that rivers required to operate the LGBs need to be considered as potential critical habitat. Currently 11 residual populations of the iBoF have been included in the LGBs. A recovery team designated under the Species at Risk Act guides the selection of rivers. The requirement for stocking-out of residual families of salmon from the LGBs increases as the program proceeds and can further increase the required potential critical habitat. It could be argued that survival of the stock is not dependent on these additional rivers and therefore they are not potential critical habitat. However, it may also be argued that inclusion of more rivers reduces the risk of loss of a lineage of salmon and therefore these rivers are also critical to hedge against a catastrophic loss of a lineage.

The case for critical habitat for recovery of the stock is not straightforward. At least three factors complicate a critical habitat designation:

First, minimum effective population (N_e) sizes for Atlantic salmon have not been established. This consideration has implications on the physical habitat size required to maintain stable populations. Although there is no consensus of what a minimum population size should be, the literature suggests N_e for freshwater fish in the 50 to 500 range (Allendorf and Ryman 1988, Hallerman 2003). While population sizes that could derive N_e values of 50 may be obtainable in many iBoF rivers, the probabilities of accumulating deleterious genes, inbreeding depression and loss of diversity increase rapidly at low population size. Consequently, low population sizes produce unacceptable risks of extirpation through genetic causes as well as through demographic and environmental stocasticity. To abate these risks, these and other authors suggest managing for larger populations. Based on the small habitat size of many rivers, larger populations are unlikely and their persistence for some 18,000 years is contradictory or conversely their extirpation and re-colonization is probable at one time or another. One possibility mitigating the low population effect is straying or immigration among adjacent populations. Even low immigration rates can effectively increase N_e and reduce the genetic threats. However, immigration, unless excessive, cannot substantially reduce extirpation through demographic and environmental instability.

An alternate view is that stability of iBoF salmon population is interdependent among rivers and that stability is dynamic and only achieved among rivers. In this structure the larger and more productive populations are expected to persist more frequently than small populations. This is known as meta-population structure (Hanski and Gilpin 1997). The derivation of requirements, i.e., number of source populations and size, for constituent populations among a meta-population that could produce an acceptable probability of persistence of the meta-population is a developing science. While the science is being developed and while meta-population structure for Atlantic salmon is debated, there is no prescriptive action for designating critical source populations in a meta-population format. Again, in the precautionary sense it may be prudent to designate residual populations, which were in fact among the larger populations in the designated unit of the iBoF, as critical to maintenance and recovery.

Second, two distinct sub-populations of iBoF salmon have been identified: an assemblage based on rivers of the Minas Basin and an assemblage based on rivers of the Chignecto Basin. This fact also begs the question of a meta-population structure for these assemblages and a recovery strategy that accommodates that structure. Again, problems arise in defining the number and sizes of constituent populations and thus the critical habitat required that could provide persistence of each of these populations. Population viability analysis for single and meta-population structures of iBoF salmon may provide valuable insight for selecting target rivers for recovery.

Third, for anadromous fish the amount of habitat required to carry a population at any given freshwater productive capacity and intrinsic rate of growth (age structure, gender proportions fecundity and freshwater life stage survival) depends on the mean and variance of survival in the marine environment. In the case of iBoF salmon, marine survival has dropped from a mean of 4.5% (Ritter 1989) to less than 1% in the Stewiacke River (Amiro and Jefferson 1996). The estimated survival from smolt to returning 1SW adult in the Big Salmon River for the 2001 smolt year class is about 0.7% (Amiro and Gibson, unpublished analysis). At these rates, very high levels of smolt production in fresh water (smolt per spawning adult), or high adult post-spawning survival (resulting in a increased number of spawning events per adult) are required to offset low levels of smolt to 1st spawning survival. As a result of the high marine mortality, recent recruitment of iBoF salmon is below freshwater carrying capacity and in this situation it is undetermined whether population viability is acutely sensitive to freshwater habitat loss.

The freshwater habitat model specifications were arbitrarily set at a mean density of 16.7 age-1 and older parr over stream grade categories from 0 to 3.0 (AWSG). This specification results in maximum parr densities of 21.5 age-1 and older parr in quality habitat, which is not as high as many historic observed densities. At lower densities, a greater percentage of age-1 parr may be expected to reach critical size for smoltification and an increase in the number of age-2 smolts per spawning adult could be expected. The maximum rate of smolt production per adult observed in the Big Salmon River from 1968 to 1973 was about 10 smolts per spawning salmon (Jessop 1975). This rate would not be sufficient to achieve replacement at 0.7% survival from smolt to 1st spawning without a high incidence of repeat spawning. Here again, it is unknown whether protection against loss of freshwater habitat quality would appreciably increase population viability for Atlantic salmon.

The temperature model used herein was not fully adequate to explain the distribution of tag recoveries for iBoF salmon. One possible explanation for this observation is that iBoF salmon have different temperature preferences than salmon in the North Atlantic from which the model was derived. Alternatively, the use of mean monthly temperatures averaged over 20 years may not capture inter-annual variability and spatial fluctuations of the preferred temperature regions. If marine survival is limiting recovery, as suggested by current return rates, then the minimum marine habitat areas suggested by SST and roughly supported by historic tag recaptures of wild iBoF post smolts (Appendix 1) may potentially be critical habitat for recovery of iBoF salmon. These minimum areas occured in July to September. A more detailed analysis of the temperature data might resolve the discrepancies between tag returns and the temperature preference model.

In summary, we have presented some methods that may be applicable to critical habitat evaluation for iBoF salmon. The exploration of the data and potential models indicates that for either maintenance or recovery, a population viability analysis needs to be undertaken. Structuring the viability analysis will involve many of the reported parameters for these stocks and venture into new areas of population and model structure. Regardless of the framework and models used, the risk acceptance to define criticality needs to be determined *a priori* or the output of the analysis can only be presented as probability profiles for persistence of the population relative to the specified habitat in question. Additionally, the complexity of the viability analysis will be directly proportional to the resolution of the habitat in question. Given the general paucity of information about the distribution of habitat within a watershed on the micro-scale, population-level responses to small habitat losses will be difficult to estimate. However, it may be possible to determine their cumulative effects at larger spatial scales given the habitat data presently available.

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Literature Cited

Allendorf, F. W.and N. Ryman. 1988. Genetic management of hatchery stocks. p141 – 160. *In* Population genetics & fishery management, N. Ryman and F. Utter (Editors). Washington Sea Grant Program, University of Washington Press, Seattle WA.

Amiro, P.G. 1987. Similarities in annual recruitment of Atlantic salmon to sport fisheries of inner Bay of Fundy rivers and stock forecasts for 1987. CAFSAC Res. Doc. 87/58, 17 p.

Amiro, P. G. 1993. Habitat measurement and population estimation of juvenile Atlantic salmon (*Salmo salar*), p.81 – 97. *In* R.J. Gibson and R.E. Cutting [ed.] Production of juvenile Atlantic salmon, *Salmo salar*, in natural waters. Can. Spec. Publ. Fish. Aquat. Sci. 118.

Amiro, P. G. and E. M. Jefferson. 1996. Status of Atlantic salmon in Salmon Fishing Area 22 and 23 for 1995, with emphasis on inner Bay of Fundy stocks. DFO Atl. Fish. Res. Doc. 96/134, 16 p. + iii.

Beland, K. F., R. M. Jordan, and A. L. Meister. 1982. Water depth and velocity preferences for spawning Atlantic salmon in Maine rivers. N. Am. J. Fish. Man. 2:11-13.

Cunjak, R. A. 1988. Behaviour and microhabitat of young Atlantic salmon (*Salmo salar*) during winter. Can. J. Fish. Aquat. Sci. 45: 2156-2160.

Cullen, L. (editor) 2003. Proceedings of Species at Risk Recovery Team Meetings – Maritimes, DFO, CSAS, Proceedings Series, 2003/??,   p, (in prep.).

Elson, P. F. 1957. Number of salmon needed to maintain stocks. Can. Fish Cult. p 19 - 23.

- 1967. Effects on wild young salmon of spraying DDT over New Brunswick forests. J. Fish. Res. Bd. Canada, 24(4), p. 731 - 767.

Gross, M.R. 1998. One species with two biologies: Atlantic salmon (*Salmo salar*) in the wild and in aquaculture. Can. J. Fish. Aquat. Sci. 55(Suppl. 1): p. 131 – 144.

Hallerman, E.M., editor. 2003. Population Genetics: Principles and Applications for Fisheries Scientists. American Fisheries Society, Bethesda, Maryland. 475 p.

Hanski, I. and M.E. Gilpin. 1997. Metapopulation biology: ecology, genetics and evolution. Academic Press, New York. 512 p.

Hayes, F. R. 1953. Artificial freshets and other factors controlling the ascent and population of Atlantic salmon in the LaHave River, Nova Scotia. Fish. Res. Bd. Can. Bull No. 99. 47 p.

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

- 1976. Distribution and timing of tag recoveries from native and nonnative Atlantic salmon (*Salmo salar*) released into the Big Salmon River, New Brunswick. J. Fish. Res. Bd. Can. 33:829-833.

- 1986. Atlantic salmon (*Salmo salar*) of the Big Salmon River, New Brunswick. Freshwater and Anadromous Division, Fisheries Research Branch, Dept. of Fisheries and Oceans, Halifax, Nova Scotia, B3J 2S7. Can. Tech. Rep. Fish. Aquat. Sci. No. 1415, 50 p.

Komadina-Douthwright, S. M., D. Cassie, and R. A. Cunjak. 1997. Winter movement of radio-tagged Atlantic salmon (*Salmo salar*) kelts in relation to frazil ice in pools of the Miramichi River. Can. Tech. Rep. Fish. Aquat. Sci. No. 2161, 66 + ix p.

Korman, J., D. R. Marmorek, G. L. Lacroix, P. G. Amiro, J. A. Ritter, W. D. Watt, R. E. Cutting, and D. C. E. Robinson. 1994. Development and evaluation of a biological model to assess regional-scale effects of acidification on Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 51:662-680.

MacCrimmon, H. R. and B. L. Gots. 1979. World distribution of Atlantic salmon *Salmo salar*. J. Fish. Res. Bd. Can. 36: 422 – 457.

Mason, C. S., B. Petrie, and B. J. Topliss. 1998. Satellite measurement of sea surface temperatures and the study of ocean climate. Can. Tech. Rep. Hydrogr. Ocean Sci. 193, 101 p.

Morantz, D. L., R. K. Sweeney, C. S. Shirvell, and D. A. Longard. 1987. Selection of microhabitat in summer by juvenile Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 44: 120-129.

Perley, M. H. 1852. The sea and river fisheries of New Brunswick. Queens Printer, Fredericton. N.B. 294 p.

Peterson, R. H. 1978. Physical characteristics of Atlantic salmon spawning gravel in some New Brunswick streams. Fish. Mar. Serv. Tech. Rep. 785, iv + 28 p.

Petrie, B. and C. S. Mason. 2000. Satellite measurements of sea-surface temperature: an application to regional ocean climate. CSAS Res. Doc. 2000/061, 24 p.

Randall, R. G. 1982. Emergence, population densities, and growth of salmon and trout in two New Brunswick streams. Can. J. Zoo. 60: 2239-2244.

Reddin, D. G. and K. D. Friedland. 1993. Marine environmental factors influencing the movement and survival of Atlantic salmon. *In* Salmon in the sea and new enhancement strategies, Derek Mills Ed. Fishing News Books, Oxford University Press, 424 p.

Rimmer, D. M., U. Paim, and R. L. Saunders. 1984. Changes in the selection of microhabitat by juvenile Atlantic salmon (*Salmo salar*) at the summer-autumn transition in a small river. Can. J. Fish. Aquat. Sci. 41: 469-475.

Ritter, J. A. 1989. Marine migration and natural mortality of North American Atlantic salmon (Salmo salar L.). Can. Man. Rep. Fish. Aquat. Sci. No. 2041. 136 p.

Spindle, A. P., S. T. Kalinowski, B. A. Lubinski, D. L. Perkins, K. F. Beland, J. F. Kocik, and T. L. King. 2003. Population structure of Atlantic salmon in Maine with reference to populations from Atlantic Canada. Trans. Am. Fish. Soc. 132: 196-209.

Saunders R. L. and J. H. Gee. 1964. Movements of young salmon in a small stream. J. Fish. Res. Bd. Can. 21: 27-36.

Symonds, P.E.K. and M. Heland. 1978. Stream habitats and behavioral interactions of underyearling and yearling Atlantic salmon, *Salmo salar*. J. Fish. Res. Bd. Can. 35: 175-183.

Verspoor, E., M. O'Sullivan, A.L. Arnold, D. Knox, and P.G. Amiro. 2002. Restricted matrilineal gene flow and regional differentiation among Atlantic salmon (*Salmo salar* L.) populations within the Bay of Fundy, Eastern Canada. Heredity, Vol. 89, Part 6, p. 465-472.

Table 1. General descriptions of temporal and spatial freshwater habitat requirements for North American Atlantic salmon for eight life stages, indicating the availability of published, science-based methods for describing stage-specific habitat use at the micro-, meso- and macro- spatial scales.

		Time		Freshwater Habitat			Reference		
Life Stage	**Age from egg deposit (months)**	**Start**	**Stop**	**Substrate**	**Locations**	**Purpose**	**Micro**	**Meso**	**Macro**
egg	0 to 6	Nov.	March	loose gravel and cobble	all river and tributaries	egg deposition and incubation	10	13	no
alevin	6 to 7	April	May	intersitial space in gravel and cobble	all river and tributaries	early development	11	11	No
fry	8 to 12	May	April	gravel, cobble and boulder	all river and tributaries	1st year growth and over wintering	9 3	4,13,14 3,12	No? No?
age-1 parr	12 to 36	May	May	cobble and boulder	all river and tributaries	2nd year growth and over wintering	9 3	4,13,14 3,12	1,8 no
age-2 parr	26 to 36	May	May	cobble and boulder	all river and tributaries	3rd year growth and over wintering	9 3	4,13,14 3,12	1,8 no
age-3 &> parr	36 to 48+	May	May	cobble and boulder	all river and tributaries	growth and over wintering	9 3	4,13,14 3,12	1,8 no
smolt	28, 38 and 50	May	July	all	lower reaches	feeding and migration	no?	5,6	1,8
adult	38, 50 and 62	Dec.	April	varied	all river – deeper water	staging for spawning and over wintering	2 7	2 7	1,8 1,8

*References: 1) Amiro 1993, 2) Beland et al.1982, 3) Cunjak 1988. 4) Elson 1967, 5) Hayes 1953, 6) Jessop 1975, 7) Komadina-Douthwright et al.1997, 8) Korman et al.1994, 9) Morantz et al.1987, 10) Peterson 1978, 11) Randall 1982, 12) Rimmer et al.1984, 13) Saunders and Gee 1964, 14) Symonds and Heland 1978

Table 2. Habitat area (number of 100 m^2 habitat units) by gradient category for 22 rivers of the inner Bay of Fundy estimated from ortho-photo maps and aerial photographs for all reaches below gradient barriers of 25%.

	Number of 100 m^2 Habitat Units by Area Weighted Percent Stream Gradient Interval											
Gradient Interval:	0-.12	121-.249	.25-.49	.5-.99	1-1.49	1.5-1.99	2-2.49	2.5-2.99	3-3.49	3.5-5.0	> 5.0 & < 25%	Total Area
Cornwallis	3,088	951	388	238	41	37	6	15	13	6	13	4,794
Gaspereau	186	2,813	752	229	18	0	0	26	0	18	0	4,042
St. Croix, Hants	462	1,101	1,036	1,201	390	250	110	41	73	49	33	4,745
Kennetcook	5,135	2,340	961	450	177	13	18	10	0	3	3	9,111
Shubenacadie	9,606	3,315	2,481	2,327	1,069	512	235	153	88	45	115	19,946
Stewiacke	13,928	3,907	3,640	3,430	1,459	438	130	32	29	16	5	27,014
Salmon, Colchester	0	3,342	6,773	2,757	427	70	61	19	3	10	5	13,468
North, Colchester	0	0	1,984	1,879	427	105	21	27	13	16	13	4,485
Chiganois	602	27	918	1,548	205	259	253	59	38	25	38	3,971
Debert	0	137	869	1,513	553	276	46	59	15	32	0	3,499
Folly	0	136	800	1,094	186	319	140	41	62	69	48	2,896
Great Village	0	0	539	820	328	397	237	87	64	74	41	2,587
Portapique	0	196	839	1,177	556	224	168	67	41	29	13	3,309
Bass, Colchester	0	0	50	390	93	38	47	25	6	20	27	696
Economy	0	375	1,335	461	115	68	16	6	5	5	0	2,386
Harrington	0	0	0	73	345	59	35	50	10	42	15	629
Parrsboro	1,042	184	475	33	0	0	9	2	0	2	0	1,747
Diligent	292	55	0	88	136	33	21	3	0	0	0	627
Apple	0	117	563	1060	300	46	17	9	0	0	0	2111
River Hebert	3,780	964	787	388	124	9	4	2	0	0	3	6,062
Maccan	2,359	1,664	3,568	1,644	657	354	139	47	78	52	25	10,587
Big Salmon	0	738	705	2,332	3,270	641	651	250	116	201	189	9,093

Table 3. Summary of the regression analysis of the relationship between the mean length of age-1 parr and the density of age-1 and older parr at 356 electrofishing sites on the Stewiacke River, NS between 1984 and 1995. Data and the fitted relationship are shown in Figure 2.

Coefficient	Value	Std. Error	p-value
a	11.330	0.225	<0.01
b	-0.759	0.043	<0.01

N = 356; $R^2 = 0.687$

Table 4. Summary of the regression analysis of the relationship between area-weighted percent surface grade and density of age-1 and older parr based on electrofishing data collected in the Stewiacke River from 1984 to 1995. Data and the fitted relationship are shown in Figure 3.

Coefficient	Value	Std. Error	p-value
ln (*a*)	3.962	0.043	<0.01
b	1.054	0.059	<0.01

N = 404; $R^2 = 0.462$

Table 5. Estimated productive capacity (number of age-1 and older parr) by gradient category for 22 rivers of the inner Bay of Fundy.

	Total Number of Parr by Area Weighted Percent Stream Gradient Interval											
Gradient Interval:	0-.12	.121-.249	.25-.49	.5-.99	1-1.49	1.5-1.99	2-2.49	2.5-2.99	3-3.49	3.5-5.0	> 5.0 & < 25%	Total
Cornwallis	8,746	5,874	5,533	4,844	867	677	87	162	102	23	12	26,927
Gaspereau	527	17,374	10,725	4,660	381	0	0	282	0	69	0	34,017
St. Croix, Hants	1,308	6,800	14,775	24,442	8,248	4,572	1,590	444	572	187	32	62,970
Kennetcook	14,543	14,453	13,705	9,158	3,743	238	260	108	0	11	3	56,223
Shubenacadie	27,205	20,475	35,383	47,357	22,607	9,363	3,397	1,657	690	172	110	168,417
Stewiacke	39,446	24,131	51,912	69,805	30,855	8,010	1,879	347	227	61	5	226,678
Salmon, Colchester	0	20,642	96,593	56,108	9,030	1,280	882	206	24	38	5	184,808
North, Colchester	0	0	28,295	38,240	9,030	1,920	304	292	102	61	12	78,257
Chiganois	1,705	167	13,092	31,504	4,335	4,736	3,657	639	298	96	36	60,265
Debert	0	846	12,393	30,791	11,695	5,047	665	639	118	122	0	62,317
Folly	0	840	11,409	22,264	3,934	5,834	2,024	444	486	264	46	47,544
Great Village	0	0	7,687	16,688	6,937	7,260	3,426	942	501	283	39	43,764
Portapique	0	1,211	11,965	23,953	11,758	4,096	2,429	726	321	111	12	56,583
Bass, Colchester	0	0	713	7,937	1,967	695	679	271	47	76	26	12,411
Economy	0	2,316	19,039	9,382	2,432	1,244	231	0	39	19	0	34,702
Harrington	0	0	0	1,486	7,296	1,079	506	542	78	161	14	11,162
Parrsboro	2,951	1,136	6,774	672	0	0	130	22	0	8	0	11,693
Diligent	827	340	0	1,791	2,876	603	304	32	0	0	0	6,773
Apple	0	723	8,029	21,572	6,344	841	246	97	0	0	0	37,853
River Hebert	10,705	5,954	11,224	7,896	2,622	165	58	22	0	0	3	38,649
Maccan	6,681	10,278	50,885	33,457	13,894	6,474	2,009	509	611	199	24	125,022
Big Salmon	0	4,558	10,054	47,459	69,155	11,722	9,411	2,708	909	769	181	156,925

Table 6. General descriptions of temporal and spatial marine habitat use for iBoF Atlantic salmon for three life stages and indication of the availability of published science based methodologies describing a habitat for that stage at the micro-, meso- and macro-spatial scales.

Life Stage	Age from egg deposit (months)	Time		Marine Habitat			Reference		
		Start	Stop	Indicator	Locations	Purpose	Micro	Meso	Macro
smolt	28, 38, and 50	May	July	no habitat indicator	estuaries and migration route	growth and maturity	no	2	2
post-smolt	+7 from smolt	May	Dec.	no habitat indicator	BoF, GoM, Scotian Shelf	growth and maturity	no	1,3	1,3
adult – 1SY	+6 from post-smolt	Dec.	Oct.	no habitat indicator	BoF, GoM, Scotian Shelf	growth and maturity	no	?	?
adult – repeat	+12 to 16 from 1SY adult	April	Oct.	unknown	unknown	growth and maturity	no	?	?
Adult – 2SY	+18 from post-smolt	Dec.	June	no habitat indicator	Nfld., G.B., Lab. Sea, W. Greenland	growth and maturity	no	1,3	1,3

*References: Amiro and Jefferson 1996, 2) Jessop 1975, 3) Jessop 1976

Table 7. Rivers that have contributed to the inner Bay of Fundy Live Gene Bank and rivers that have been recipient of Live Gene Bank stocking (to November 2002).

Contributing Rivers	Recipient Rivers
Gaspereau	Gaspereau
Stewiacke	Stewiacke
Great Village	Salmon (Col.)
Economy	Debert
Harrington*	Chiganois
Portapique	Folly
Folly	Big Salmon
Debert	Petitcodiac
Big Salmon	Demoiselle
Black*	Parrsboro
Irish*	

* Genetic status undetermined at the time of publication.

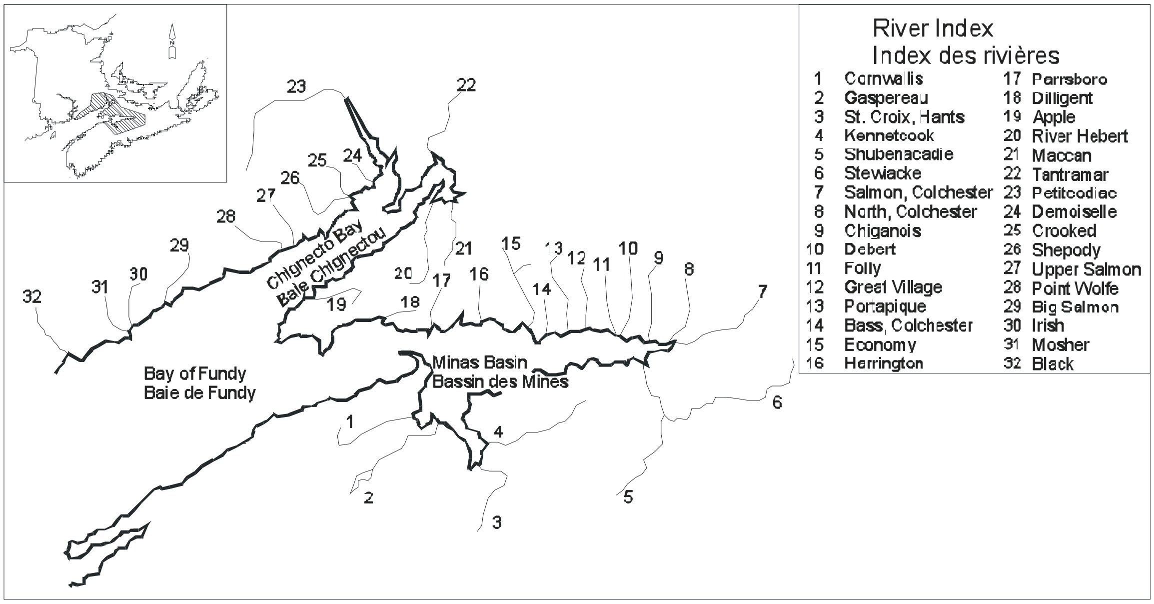


Figure 1. Map of the known Atlantic salmon rivers of the inner Bay of Fundy.

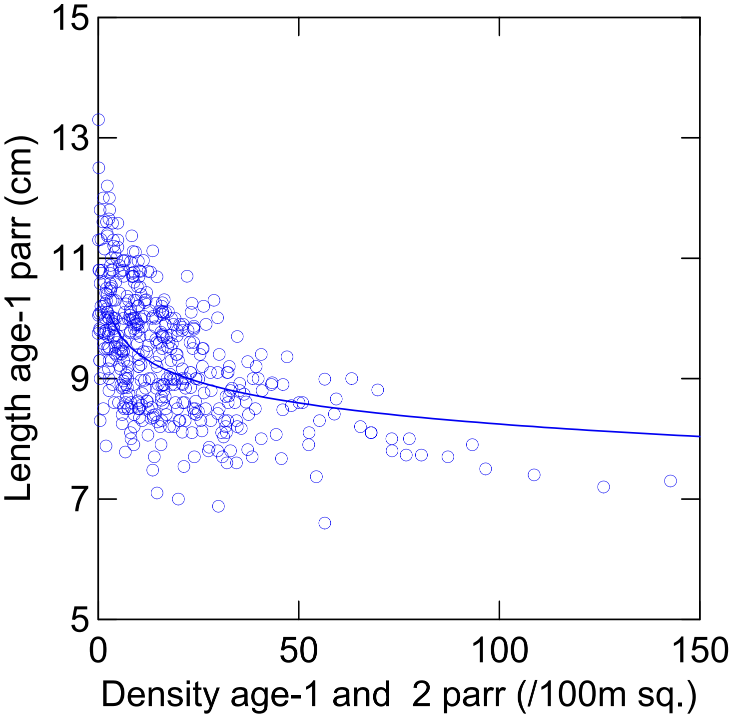


Figure 2. The relationship between length of age-1 Atlantic salmon parr and the density of age-1 and 2 parr in the Stewiacke River 1984 to1995.

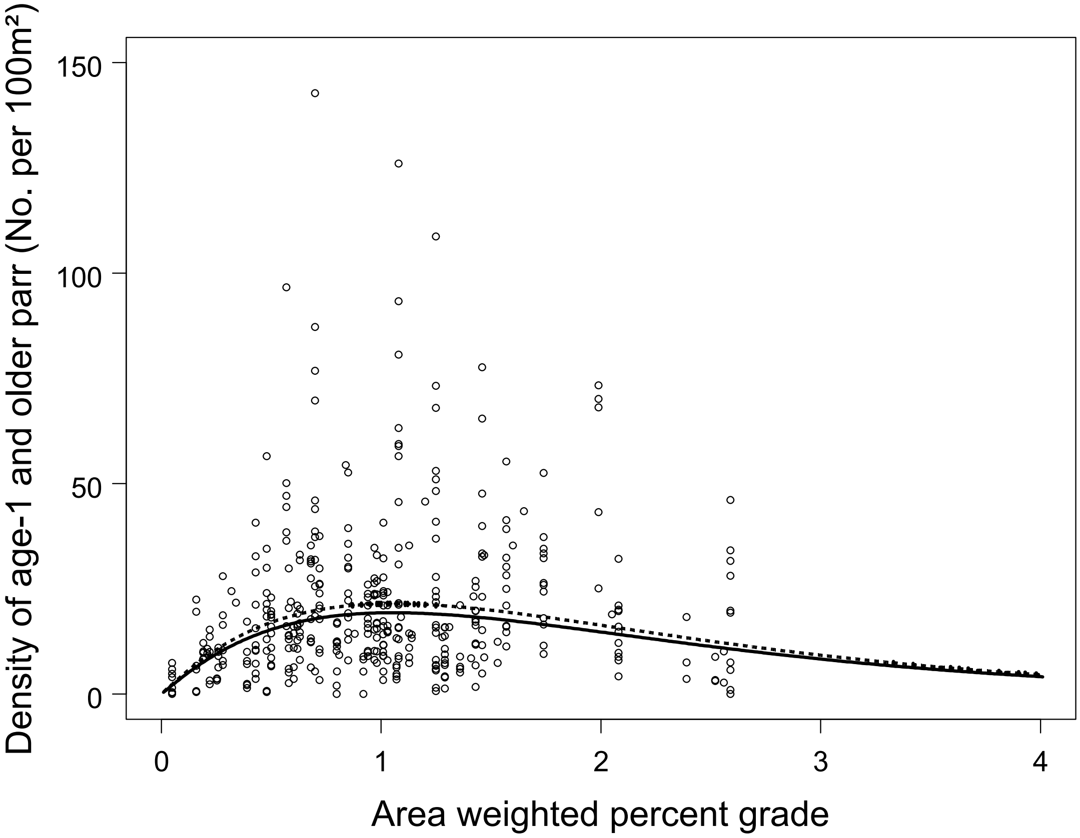


Figure 3. Fitted and observed relationship between the density of age -1 and older juvenile Atlantic salmon and stream reach gradients for the Stewiacke River from for 1984 to 1995. Stream gradients (AWSG) are weighted by areas of sub-unit grades measured at the reaches where electrofishing was conducted (Amiro 1993). The solid line is the fitted relationship (equation 3; Table 4). The dashed line is the model calibrated to a mean density of 16.7 parr over gradients from 0 to 3 AWSG that was used to estimate productive capacity by stream reach.

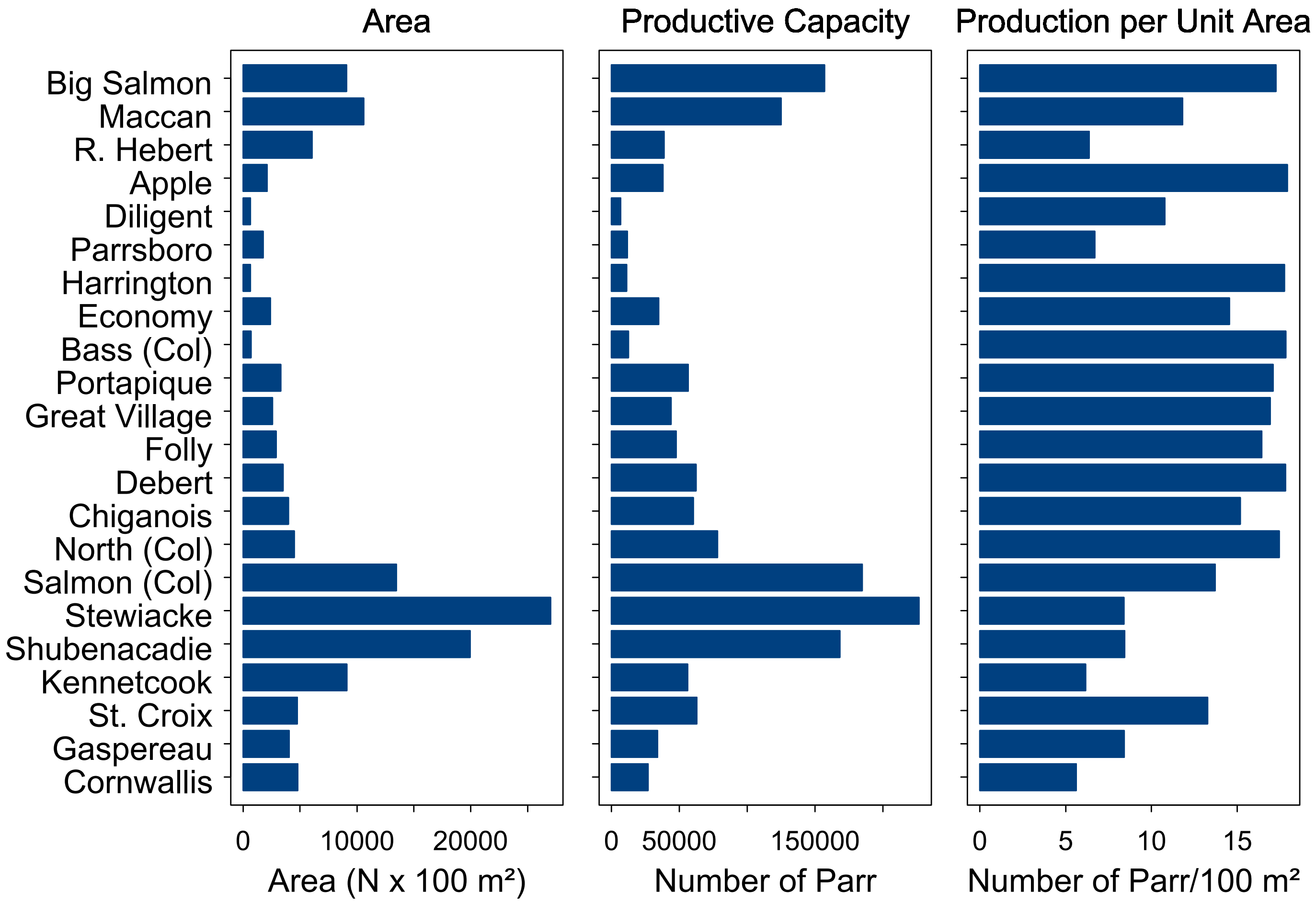
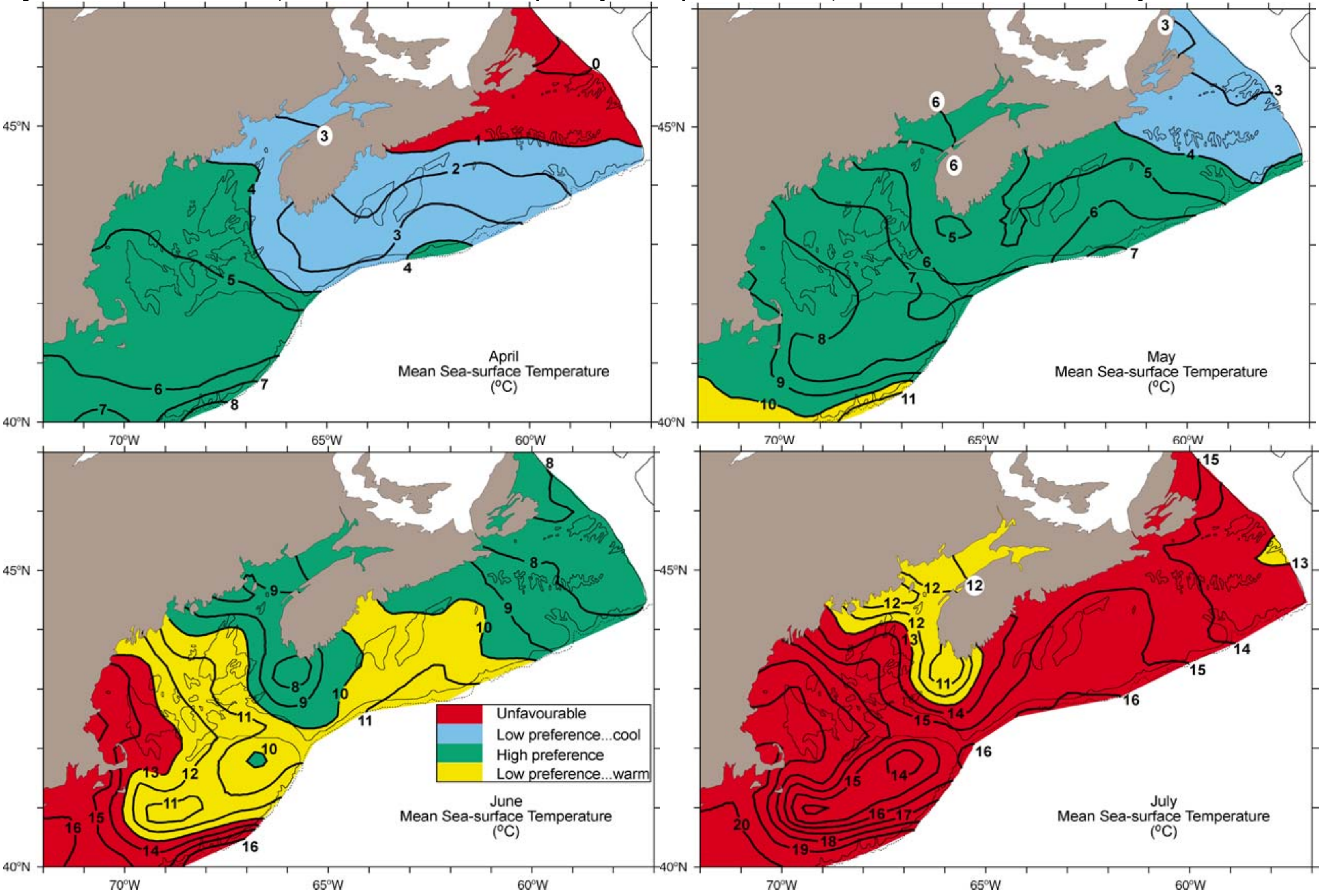
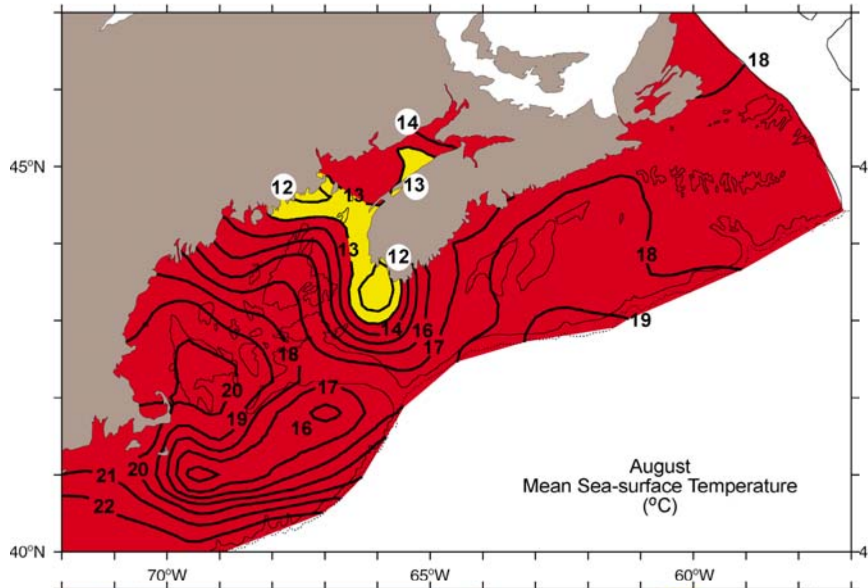
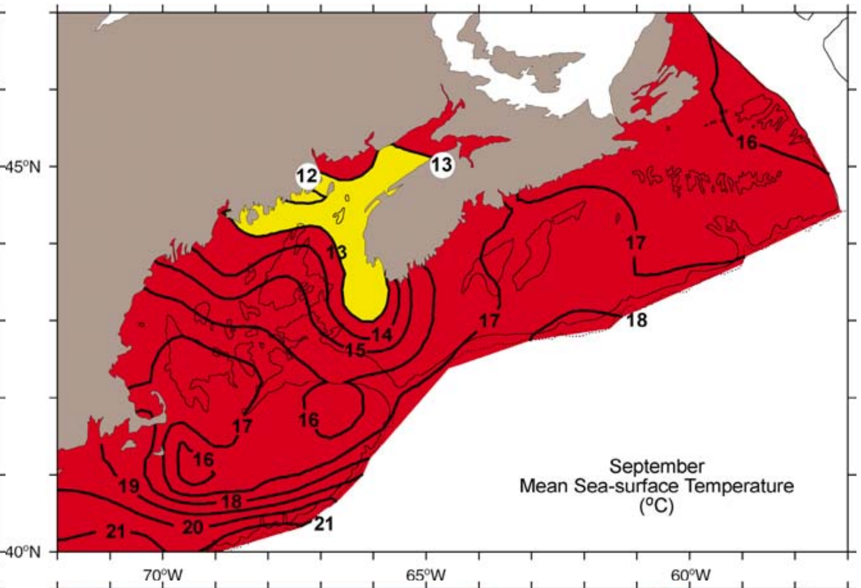


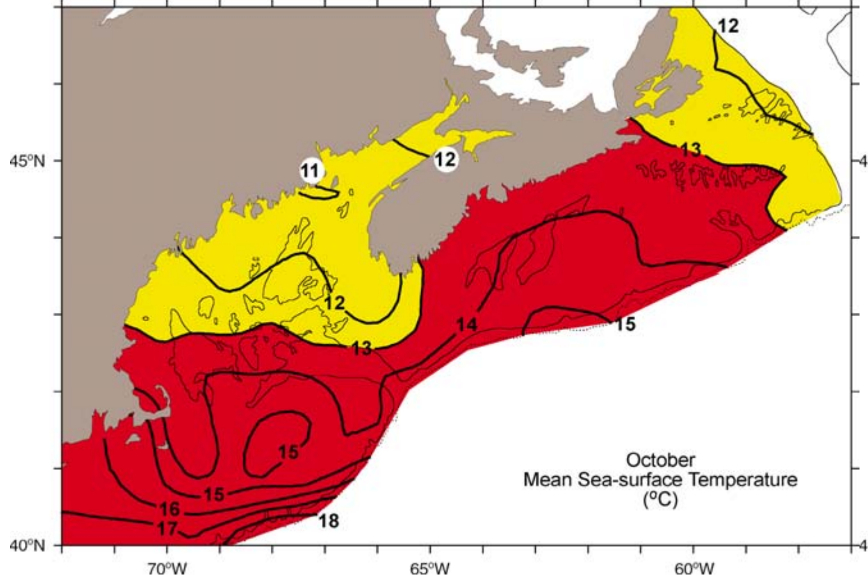
Figure 4. Area, productive capacity of age-1 and older Atlantic salmon parr and production of parr per unit area for 22 inner Bay of Fundy rivers, determined using area, grade (measured from ortho-photo maps) as a proxy for habitat quality for stream reaches and Equations 1 and 4 in text. (Col is an abbreviation for Colchester Co.).

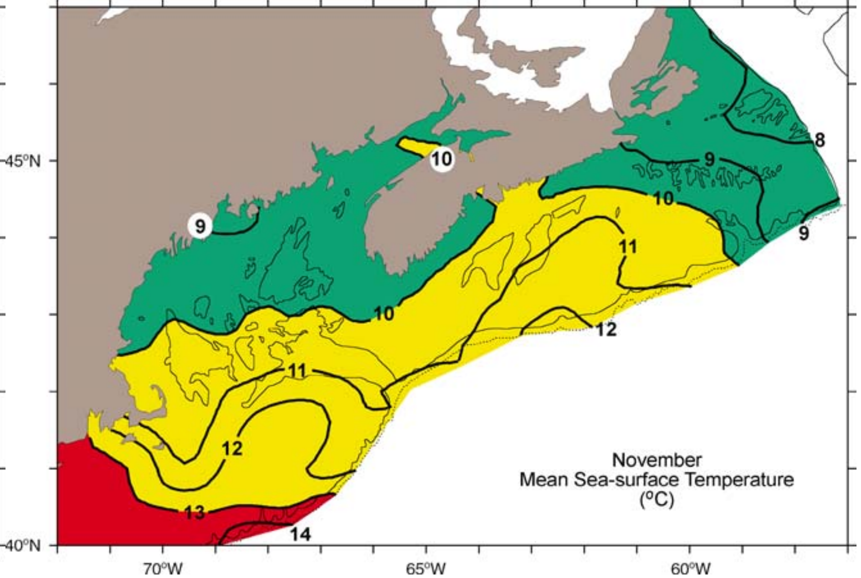
Figures 5 to 16 Atlantic salmon preference area as indicated by average monthly sea surface temperatures from satellite information gathered 1981 to 2000.

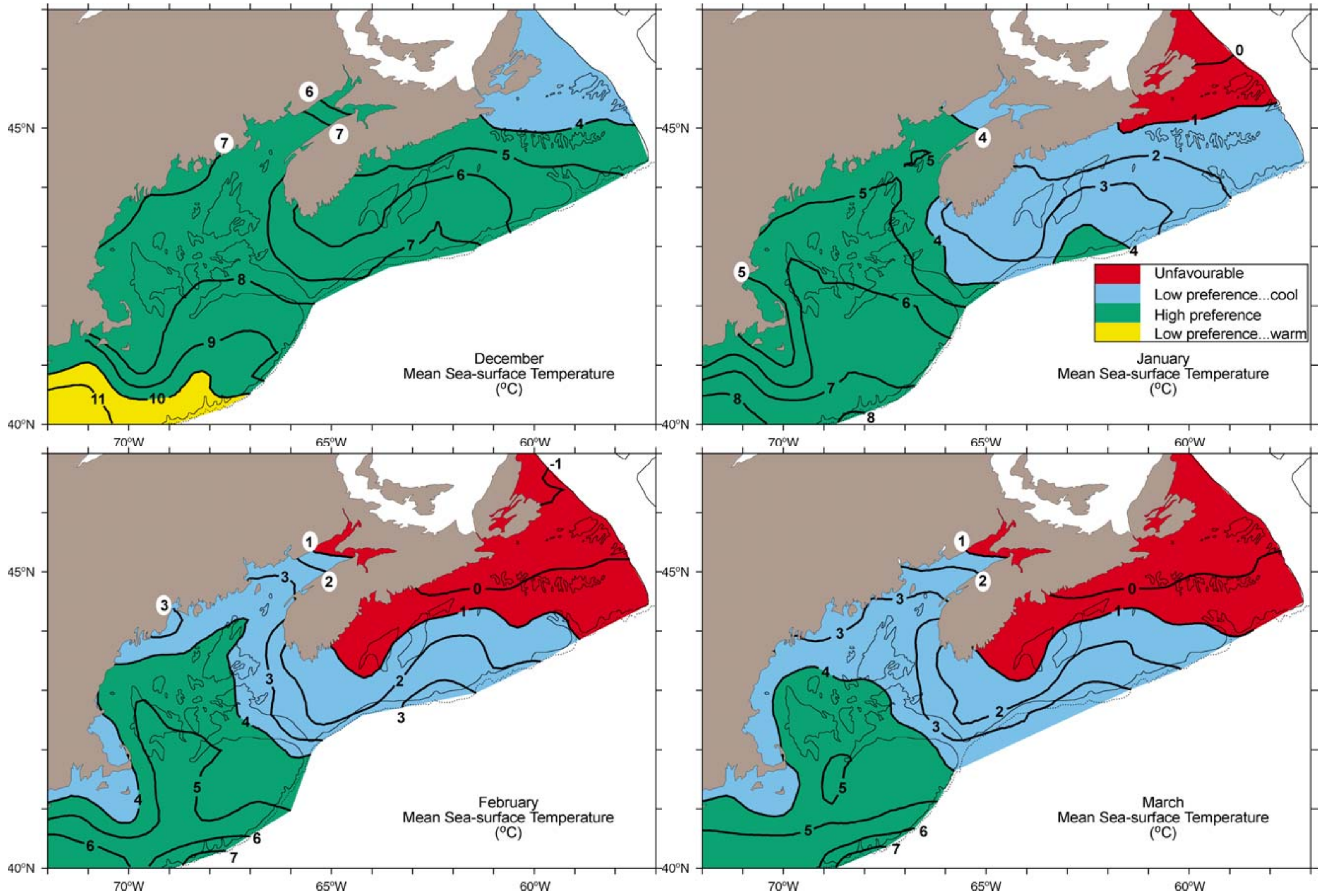



August
Mean Sea-surface Temperature
(°C)


September
Mean Sea-surface Temperature
(°C)


October
Mean Sea-surface Temperature
(°C)


November
Mean Sea-surface Temperature
(°C)


December
Mean Sea-surface Temperature
(ºC)
January
Mean Sea-surface Temperature
(ºC)
February
Mean Sea-surface Temperature
(ºC)
March
Mean Sea-surface Temperature
(ºC)
🟥 Unfavourable
🟦 Low preference...cool
🟩 High preference
🟨 Low preference...warm
45ºN
40ºN
70ºW
65ºW
60ºW

Appendix 1

Locations and numbers of recaptures of tagged wild and hatchery Big Salmon River post smolts by month of recapture.