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Estimation of exploitation and migration rates of Atlantic cod (*Gadus morhua*) in NAFO Subdiv. 3Psc and Divs. 3KL during 1997 and 1998 based on tagging experiments.

by

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Abstract

Mark-recapture experiments can be used to estimate the abundance of fish inhabiting inshore regions where rough bottom and steep bathymetry preclude use of other common survey methods such as trawling and acoustics. Recaptures of tagged fish can be used to estimate the exploitation rate of the fishery and the exploitation rate can, in conjunction with estimates of the total landings by the commercial fishery, then be used to estimate stock size. Estimation of exploitation rates requires estimates of the number of tagged fish available for capture. This number changes with time-since-release because of tag loss and migration of tagged fish out of the fishing region, as well as natural mortality and removals by the fishery. In this paper we use a simple cyclical-seasonal migration model to estimate migration rates of cod between Placentia Bay off the south coast of Newfoundland (3Psc), and the inshore off the northeast coast of Newfoundland (3KL). We also use the model to estimate exploitation rates for the 1997 and 1998 fisheries in these regions.

Our results indicate that exploitation of cod in Placentia Bay was 7% during January-June 1997, and 4% in the remainder of the year. Exploitation was also very low during the first half of 1998 in Placentia Bay, but increased to 10% in the second half of the year. Exploitation in 3KL was very low in 1997 and the first half of 1998 due to lack of fishing activity, but in the second half of 1998 exploitation was estimated to be 6% for cod in northern 3L and 3K, and 12% for cod in southern 3L.

Résumé

Les missions du marquage-recapture peuvent être utilisées pour estimer l'abondance des poissons dans les zones côtières où les fonds accidentés et les pentes abruptes interdisent l'utilisation d'autres méthodes de relevé courantes, comme les relevés par chalutage et les relevés acoustiques. La recapture de poissons marqués peut servir à estimer le taux d'exploitation de la pêche et le taux d'exploitation, utilisé de pair avec des estimations des débarquements totaux de la pêche commerciale, peut ensuite permettre d'estimer l'effectif des stocks. L'estimation des taux d'exploitation exige d'estimer le nombre de poissons marqués pouvant être recapturés. Ce nombre varie avec le temps écoulé depuis le marquage car il y a perte d'étiquettes et migration de poissons marqués à l'extérieur de la zone de pêche, en plus de la mortalité naturelle et de la récolte par la pêche. Dans ce document, nous avons utilisé un modèle cyclique saisonnier simple pour estimer les taux de migration de la morue entre la baie Placentia, sur la côte sud de Terre-Neuve (3Psc), et la zone côtière du nord-est de la province (3KL). Nous avons aussi appliqué le modèle à l'estimation des taux d'exploitation des pêches de 1997 et 1998 réalisées dans ces régions.

Nos résultats montrent que le taux d'exploitation de la morue de la baie Placentia était de 7% de janvier à juin 1997 et de 4% pendant le reste de l'année. Le taux d'exploitation était aussi très faible pendant la première demie de 1998 dans la baie Placentia, mais s'est élevé à 10% pendant la deuxième demie de l'année. Le taux d'exploitation en 3KL était aussi très faible en 1997 et pendant la première demie de 1998, suite à une pêche réduite,

mais, dans la deuxième demie de 1998, il a été estimé à 6% pour la morue dans le nord de 3L et 3K et à 12% dans le sud de 3L.

1 Introduction

Estimation of the abundance of inshore fish stock components is often difficult because the near-shore topography causes problems when using common survey methods, e.g. trawl and acoustic surveys. Fish tagging experiments offer a solution to this problem because the number of tag-returns from a fishery can be used to estimate the exploitation rate of the fishery, even in difficult near-shore regions. The exploitation rate can then be used, in conjunction with estimates of the total landings by the fishery, to estimate stock size. Estimation of exploitation rates requires estimates of the number of tagged fish available for capture and the reporting rate of tagged-fish that are caught. Fishermen are encouraged, using rewards, to return tags; however, not all tagged fish caught by the fishery are reported. The number of tagged fish available for capture changes with time because of tag loss and migration of tagged fish out of the fishing region, as well as natural mortality and removals by the fishery. Estimation of tag loss and reporting rates is considered in Cadigan and Brattey (1999). In this paper we use a simple cyclical-seasonal migration model to estimate migration rates of cod between Placentia Bay off the south coast of Newfoundland (3Psc), and the inshore off the northeast coast of Newfoundland (3KL). We also use the model to estimate exploitation rates for the 1997 and 1998 fisheries in these regions.

Tagging studies have provided useful information about cod movement patterns, but within NAFO subdivision 3Ps stock structure is complex and poorly understood. At least five stock components are thought to contribute to the fishery in 3Ps (Taggart et al 1995; Brattey 1996 and refs therein) and there is extensive mixing with adjacent stocks (D'Amours et al. 1994; Rollet et al. 1994; Campana et al 1998). Recent tagging studies have shown a seasonal spring-summer movement of some cod across the stock management boundary from 3Ps into 3L with a return migration in the fall (Brattey 1999; Brattey et al. 1999). However, more detailed quantitative information is required on stock structure and migration patterns, together with estimates of exploitation and survival rates to improve the reliability of the assessment of the 3Ps cod stock.

In this paper we develop a simple migration model for cod movements between 3Psc (Placentia Bay) and 3L, and also for cod movements between 3L and 3K. We estimate the migration rates using tag-returns from releases in 1997 and 1998, and use the migration model to estimate exploitation rates in these regions. The migration model is annually cyclic, where fish in 3Psc and 3L move north in the first half of the year, then return in the second half of the year. We use a similar approach to Schwarz at al. (1993) for modelling migration. The exploitation rate is essentially estimated as the fraction of tags returned by the fishery, compared to the number available to the fishery. We need to know what fraction of 3Psc tagged cod are available to the 3KL fishery in order to determine the exploitation rate using 3Psc tag-returns from 3KL. This is determined, in part, by the migration rates between these two regions. Also, we need to know what fraction of tagged fish released in

3Psc leave this area within the fishing season so that we can estimate 3Psc exploitation rates based on tag-returns from this area. The migration model we develop is fairly simple and has only twelve cells (three areas and four six-month time periods); our data are not extensive enough to allow fitting a more complex migration model. However, the model gives more reasonable estimates of exploitation than could be obtained assuming no migration.

2 Data

We analyze the returns of 21 tagging experiments, conducted in 3Psc and 3KL during 1997-1998 (see Table 1 in the **Appendix**). The location of these experiments are shown in Figures 1a-c in the **Appendix.** Most cod for tagging were captured with hand-lines, but some trap-caught and otter-trawled cod were also tagged. The length of each cod (nearest cm) was recorded. Only cod with a fork length exceeding 45 cm and in excellent condition were tagged and released. Further details on the tagging experiments are given in Brattey et al. (1999). Fishermen were encouraged, using rewards, to return tags. Cod were tagged with single yellow ($10 reward), double yellow ($20 reward for returning both tags) or single pink tags ($100 reward). During most tagging experiments the proportion of single, double, and high reward tags applied was approximately 0.45:0.45:0.1. The different tag types are used to analyze tag loss and reporting rates (see Cadigan and Brattey, 1999).

3 Model

The migration model is cyclic; that is, all fish that migrate north from 3Psc to 3KL and survive exploitation are assumed to return south in the same year. To simplify estimation we combine tag-returns for all gear types and cod lengths, and ignore the effects these factors have on exploitation. We also combine all tag-returns each year into two time periods to simplify modelling. June 15th is the dividing point between the two time periods. This captures the essential migration cycles of cod between 3Psc and 3KL; hence, our model allows some fish to move north from 3Psc to 3KL during January - June 15. All 3Psc migrants in 3KL that survive exploitation are assumed to return to 3Psc in the second half of the year. We have two years of tag-returns, so our model has four time intervals, which we denote as $t = 1, .., 4$. The number of cod tagged and released in each region and time interval is shown in Figure 2. Fitting a more detailed model requires more data than we have available. This is because tagging experiments were not conducted for all cells in our model, and because of the lack of a commercial fishery in 3KL in 1997 and the first half of 1998, and the low levels of effort in 3Psc in the first half of 1998 (see Figure 3).

We assume that fish migration occurs as a pulse at the end of each time period (half year) and that exploitation, tag loss, and natural mortality are experienced continuously within each time period. We consider three regions for migration: Placentia Bay, Southern 3L, and

Northern 3L and 3K. For simplicity we refer to these regions as 1, 2 and 3; that is,

$$\begin{array}{ll} \text{Region 1:} & \text{Placentia Bay} \\ \text{Region 2:} & \text{Southern 3L} \\ \text{Region 3:} & \text{Northern 3L and 3K} \end{array}.$$

Southern 3L consists of units 3Lf, 3Lj, 3Lq and 3Lb, which is the inshore area covering St. Mary's Bay up to and including Trinity Bay. Northern 3L and 3K includes Bonavista Bay and areas northwards. The migration model we use assumes that in the first half of the year indigenous fish move from region 1 to 2, and from region 2 to 3. In the second half of the year all the migrants are assumed to return to their place if origin. Indigenous fish in Northern 3L and 3K are not assumed to migrate out of this region, at any time. Diagrams of the migration routes are presented in Figures 4-6. The arrows describe the basic behavior of the migration model. We used information from 1077 tags returned from experiments conducted in 3Psc and 3KL. Only 15 of these tags were returned in regions and time periods not included in our model. For example, one tag from a release in region 1 in Jan-Jun 15, 1997 was returned from region 3 in that same time period. Our model does not accommodate that movement. These tag-returns were removed from our analysis, and not considered in inferences.

The time of capture was missing for some tag-returns, or only the month of capture was reported. Approximately 20% of the tag-returns had missing times. We can narrow down the time of capture for tag-returns with no capture month reported using the date of release and the date the tag was returned. Using this information we were able to allocate most of the tags with missing times into the correct semi-year time period. For a small fraction of the tags we could only determine the year of capture, and in these cases we allocated the tags to time periods in proportion to the temporal distribution of known semi-year capture times. We stratified this allocation procedure by area of release, area of return, tag type, and experiment. Future research into time interval-censored modelling of tag-returns should produce a better solution to this problem; however, we feel the approach we have taken here is reasonable.

We describe the migration model mathematically in three steps:

Step 1. Model tag loss and natural mortality.

Step 2. Model exploitation by the commercial fishery.

Step 3. Model migration.

3.1 Tag loss

There are four types of tagged fish in the population at any time, which we index using k :

$$i = \begin{cases} 1, \text{ for a single low-reward (SLR) return from a SLR release,} \\ 2, \text{ for a SLR from a double release} \\ 3, \text{ for a double return,} \\ 4, \text{ a high-reward return.} \end{cases}.$$

Let $M_{ij}^{ok}(t)$ be the number of type k tagged fish at the start of time t in region j, from tagged fish released in region i at time t_x, $t \geq t_x$. Let $M_{ij}^{k}(t)$ denote the number at the end of time t. Also, let $\exp(-\phi)$ denote the semi-annual tag retention rate, and $\exp(-m)$ denote the known semi-annual "natural" survival rate. We collect these latter two terms into $\nu = \exp(-m-\phi)$. The number of type k tagged fish at the end of time period t is

$$
\begin{aligned}
M_{ij}^{k}(t) &= \nu M_{ij}^{ok}(t), \ k = 1, 4, \\
M_{ij}^{2}(t) &= \nu M_{ij}^{o2}(t) + 2\nu \{1 - \exp(-\phi)\} M_{ij}^{o3}(t), \\
M_{ij}^{3}(t) &= \nu \exp(-\phi) M_{ij}^{o3}(t).
\end{aligned}
$$

Note that $M_{ii}^{ok}(t_x)$ is the number of tagged fish released. Recall that these numbers are shown in Figure 2 for all tag types; that is, for $\sum_k M_{ii}^{ok}(t_x)$. These tag-loss equations are described more fully in Cadigan and Brattey (1999). We use the estimates of tag loss and reporting rates presented in Cadigan and Brattey (1999). We converted their weekly tag loss rates to semi-year rates by multiplying by 26. If t is the first time period following the time of release, t_x, then we replace ν by $\nu^{1/2}$ and use the average tag loss for the first 26 weeks, which is $\phi = 15\phi_1 + 11\phi_2$, where ϕ_1 and ϕ_2 are the weekly short-term and long-term tag loss rates presented in Cadigan and Brattey (1999; see Table 4). Replacing ν by $\nu^{1/2}$ is based on the approximation that the tagged fish were released at the middle of the first time period. For other t we use the long-term tag loss rate (ϕ_2) presented in Cadigan and Brattey (1999). Note that $\phi_1 > \phi_2$.

3.2 Exploitation and migration

We can model exploitation and fish movements easily using migration transition matrices. We illustrate the use of these transition matrices in our model using single tagged fish. The model can be used for other tag types in a straight-forward manner. For simplicity we drop the superscript k notation in M^{ok}. Let $q_{j \to k}^{i}$ denote the rate at which fish released in region i migrate from region j to region k. Let $1 - \mu_{it}$ be the fraction of tagged fish surviving exploitation in region i and time period t.

The number of tagged fish from a Placentia Bay release in $t = 1, 3$ is modelled as

$$
\begin{bmatrix} M_{11}^{o}(t+1) \\ M_{12}^{o}(t+1) \\ M_{13}^{o}(t+1) \end{bmatrix} = \begin{bmatrix} 1 - q_{1\to 2}^{1} & 0 & 0 \\ q_{1\to 2}^{1} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} (1-\mu_{1t})M_{11}(t) \\ (1-\mu_{2t})M_{12}(t) \\ (1-\mu_{3t})M_{13}(t) \end{bmatrix}. \tag{1}
$$

These equations can also be written as

$$
\begin{aligned}
M_{11}^{o}(t+1) &= (1 - q_{1\to 2}^{1})(1-\mu_{1t})M_{11}(t), \\
M_{12}^{o}(t+1) &= q_{1\to 2}^{1}(1-\mu_{1t})M_{11}(t), \\
M_{13}^{o}(t+1) &= 0.
\end{aligned}
$$

In this model $(1 - q_{1\to 2}^{1}) \times 100\%$ of the Placentia Bay releases that are in Placentia Bay and survive exploitation (e.g. $(1-\mu_{1t})M_{11}(t)$) during January-June 15th ($t = 1, 3$) stay in Placentia Bay during June 16th-December ($t = 2, 4$); that is, $1 - q^1_{1\to2}$ is the fraction of the Placentia Bay releases that do not migrate to Southern 3L. The number of fish that do migrate from Placentia Bay to Southern 3L is $q^1_{1\to2}(1 - \mu_{1t})M_{11}(t)$. No fish are assumed to migrate between Placentia Bay and Northern 3LK which is why $M^o_{13}(t + 1) = 0$. All Placentia Bay fish in Southern 3L are assumed to return to Placentia Bay at the end of December each year, and the migration matrix for this movement is

$$\begin{bmatrix} M^o_{11}(3) \\ M^o_{12}(3) \\ M^o_{13}(3) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} (1-\mu_{1t})M_{11}(2) \\ (1-\mu_{2t})M_{12}(2) \\ (1-\mu_{3t})M_{13}(2) \end{bmatrix}. \quad (2)$$

The Southern 3L transition matrices are

$$\begin{bmatrix} M^o_{21}(t+1) \\ M^o_{22}(t+1) \\ M^o_{23}(t+1) \end{bmatrix} = \begin{bmatrix} 1-q^1_{1\to2} & 0 & 0 \\ q^1_{1\to2} & 1-q^2_{2\to3} & 0 \\ 0 & q^2_{2\to3} & 0 \end{bmatrix} \begin{bmatrix} (1-\mu_{1t})M_{21}(t) \\ (1-\mu_{2t})M_{22}(t) \\ (1-\mu_{3t})M_{23}(t) \end{bmatrix}, \ t = 1, 3, \quad (3)$$

and

$$\begin{bmatrix} M^o_{21}(3) \\ M^o_{22}(3) \\ M^o_{23}(3) \end{bmatrix} = \begin{bmatrix} 0 & q^2_{2\to1} & 0 \\ 0 & 1-q^2_{2\to1} & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} (1-\mu_{1t})M_{21}(2) \\ (1-\mu_{2t})M_{22}(2) \\ (1-\mu_{3t})M_{23}(2) \end{bmatrix}. \quad (4)$$

The $q^2_{2\to1}$ term in (4) allows for the return migration of Placentia Bay fish that were tagged in June 15th to December in southern 3L. We do not know the origins of fish tagged in 3L during this time period, although we feel that it is quite likely that some of these fish are from Placentia Bay. We have actually allowed for different transition matrices, depending on when fish were tagged in Southern 3L. If fish were released in the first part of the year then we assume these fish do not migrate into Placentia Bay; that is, when $t_x = 1$ or 3 then we constrain $q^2_{2\to1}$ to be zero. This is because of our basic assumption that fish migrate southwards only in the second part of the year. However, no fish were tagged in Southern 3L for $t_x = 1, 3$ (see Figure 2), so this constraint has no effect on our estimates. Our inferences about $q^2_{2\to1}$ are based solely on tagging of a mixed population.

The migration transition matrix we use for Northern 3L and 3K fish is simple. It is a matrix of zeros, except for a one in row three and column three. We use the same matrix for the first and second half of the year. Strictly speaking we should allow for a southward migration of fish tagged in Northern 3L and 3K during June 16 to December, because Southern 3L fish are in Northern 3KL at this time. However, the tag-returns for the experiments we have examined show only one recapture outside of Northern 3KL (region 3) from releases in Northern 3KL at $t_x = 2$. This suggests that our estimate of $q^3_{3\to2}$ will be approximately zero, and in unreported results this is the case.

3.3 Estimation and inferences

There are a total of 15 parameters to estimate: 3 migration parameters, and the 12 exploitation rates. We estimate fishery exploitation rates in each of the three regions for the four semi-annual time periods in 1997-1998. These estimates are based on the tag-returns from the fisheries in 3Psc and 3KL in 1997 and 1998. We assume an overdispersed Poisson stochastic model for tag-returns. Let R_{ijt}^k denote the number of returns of type k tagged fish at the start of time t in region j from release i. The expected value of R_{ijt}^k is modelled as

$$E\left\{R_{ij}^k(t)\right\} = \lambda^k \mu_{jt} M_{ij}^k(t) = \theta_{ijt}^k,$$

where $\lambda^k = \lambda_1$ for type 1 and 2 tags, $\lambda^k = \lambda_2$ for type 3 tags, and $\lambda^k = 1$ for type 4 tags. These reporting rates are estimated in Cadigan and Brattey (1999), and are treated as fixed here. The variance is

$$Var\left\{R_{ij}^k(t)\right\} = \sigma\theta_{ijt}^k.$$

We estimate parameters using quasi-likelihood (see McCullagh and Nelder, 1989). The fit function, or deviance measure, we use is

$$Q = \sum_{k=1}^{4}\sum_{t_x=1}^{4}\sum_{t=t_x}^{4}\sum_{i=1}^{3}\sum_{j=1}^{3} 2\left[r_{ij}^k(t)\log\left\{r_{ij}^k(t)/\theta_{ijt}^k\right\} - \left\{r_{ij}^k(t) - \theta_{ijt}^k\right\}\right]/\sigma. \tag{5}$$

Parameter estimates based on maximizing (5) are identical to maximum likelihood estimates based on the Poisson distribution. The difference in using (5) compared to the Poisson distribution is in terms of inferences. The σ parameter allows for variability greater than the Poisson assumption, which is $Var(R) = E(R)$. This approach for modelling tag return data has been considered by others; for example, see Myers and Hoenig (1997).

Our model involves many parameters, and inferences for particular parameters need to be adjusted for uncertainty arising from the other unknown parameters. We use the profile quasi-likelihood (PQL) function for this purpose. The profile likelihood function is widely recommended for inference when nuisance parameters are present (see Cox and Barndorff-Nielsen, 1994), and has also been recommended for quasi-likelihood inferences (see Nelder and Pregibon, 1987). The PQL can be used to construct confidence intervals as follows. Under the null hypothesis that the population value for a parameter is specified, for example $\mu_{43} = c$ where c is known, then

$$Q(\mu_{43} = c) - \hat{Q} \overset{asy}{\sim} \chi_1^2,$$

where $Q(\mu_{43} = c)$ is the value of (5) when μ_{43} is fixed at the value c, and the other exploitation and migration parameters are equal to their quasi-likelihood estimators obtained for the fixed value of μ_{43}. A $(1-\alpha)100\%$ confidence interval for μ_{43} is approximately the two values of μ_{43} that solve $\Lambda(\mu_{43}) - \hat{\Lambda} = \chi_{1,1-\alpha}^2$, where $\chi_{1,1-\alpha}^2$ is the $1-\alpha$ percentile of a χ_1^2 distribution. Examples of these procedures are presented in Nelder and Pregibon (1987). Inferences about other parameters can be obtained in an analogous manner.

4 Results and Discussion

Estimates of the migrations rates of tagged fish are presented in Table 2. The Placentia Bay

Table 2. Migration rate estimates.

Parameter	Estimate
$q^1_{1\to 2}$	0.070
$q^2_{2\to 3}$	0.534
$q^2_{2\to 1}$	0.540

migration route, and estimated migration rates, are shown in Figure 4 in the **Appendix**. The estimates suggest that approximately 7% of tagged fish in Placentia Bay during January to June 15th migrate to Southern 3L. If we assume complete mixing of tagged fish in Placentia Bay during this period then our results suggest that 7% of the biomass in Placentia Bay in the first half of the year migrates to Southern 3L. The Southern 3L migration route and estimated migration rates are shown in Figure 5. These results suggest that approximately 50% of the fish tagged in Southern 3L during January to June 15th migrate north. In the second half of the year approximately 50% of tagged fish in Southern 3L migrate south to Placentia Bay. Presumably this is due to tagging of mixed stock (3PS and 3L) components in 3L after June. The migration model we used for Northern 3L and 3K tagged fish is shown in Figure 6.

Exploitation rate estimates are presented in Table 3 , and are also shown in Figure 7. We

Table 3. Exploitation rate estimates.

Region	Semi-year	Estimate
Placentia Bay	Jan-Jun 15 1997	.071
	Jun 16-Dec 1997	.043
	Jan-Jun 15 1998	.004
	Jun 16-Dec 1998	.097
Southern 3L	Jan-Jun 15 1997	.001
	Jun 16-Dec 1997	.010
	Jan-Jun 15 1998	.000
	Jun 16-Dec 1998	.123
Northern 3L and 3K	Jan-Jun 15 1997	.000
	Jun 16-Dec 1997	.004
	Jan-Jun 15 1998	.004
	Jun 16-Dec 1998	.062

actually estimated log exploitation rates, and transformed the estimates to those in Table 3. The exploitation rates are low in 3KL during 1997 and the first half of 1998. During this time period there were few reported landings other than those from the sentinel fishery. The food fishery, index fishery, and sentinel fishery resulted in much higher exploitation in the last half of 1998. The exploitation rates in Placentia Bay during 1997 were higher because of the commercial fishery there (see Figure 3). The fishery was purely competitive in 1997, and much of the quota was caught before mid June. In 1998 there was an individual quota (IQ) fishery in Placentia Bay, which did not start until the end of June, with much of the fishing occurring in the fall (see Figure 3). This is why the exploitation rate estimate for Placentia Bay during the first half of 1998 is low.

PQL confidence intervals for the exploitation rates in the second half of 1998 are presented in Table 4. The estimate of overdispersion used for these intervals is $\hat{\sigma} = 2.07$. This estimate

Table 4. Exploitation rate 95% confidence intervals.

Region	Time	Lower	Upper
Northern 3L and 3K	Jun 16-Dec	0.024	0.089
Southern 3L	Jun 16-Dec	0.049	1
Placentia Bay	Jun 16-Dec	0.080	0.105

is the deviance, $\hat{Q}$, divided by the error degrees of freedom (see McCullagh and Nelder, 1989). The error degrees of freedom are 112. The interval for Placentia Bay is quite small, which is related to the extensive tagging program that has been conducted there in 1997 and 1998. A smaller number of tagging experiments have been conducted in 3KL, especially prior to the 1998 index fishery, and the result is wider confidence intervals. The confidence interval for exploitation in Southern 3L in the latter half of 1998 exploitation is quite wide. It is actually a 95% lower confidence interval. All exploitation rates > 0.05 in Southern 3L are reasonably consistent with the observed tag-returns, as measured using PQL and the migration model. We consider this in more detail below.

To assist in understanding the migration model we consider two examples of how the model works. The first example is presented in Figure 8. It involves following the single-tagged cod released during January to June 15th in Placentia Bay in 1997. We examine how these fish migrate, in our model, throughout the four time periods and three regions, and compare the model-predicted tag-returns with the observed tag-returns. The number of tagged fish released is indicated in the rounded-rectangle. In each box we show the number of tagged fish ($\mathbf{M}$) at the end of each time period, and the modelled predicted catch ($\mathbf{C}$) of these tagged fish. These predictions are simply obtained using the exploitation rates in Figure 7. The number of tags reported ($\mathbf{R}$) from the predicted catch is obtained using the regional specific reporting rates shown at the top of the figure. The observed number of returned tags is shown in parentheses, following the model predicted number. The numbers along the arrows are the predicted number of tagged fish that migrate from region to region. These are $(\mathbf{M} - \mathbf{C})\times$ the fractions shown in Figures 4-6. The second example we consider (see Figure 9) is based on the tagged fish released in Southern 3L, June 16-December 31st, 1997. These examples demonstrate how the model works, and that the predictions, while variable, are consistent with the observed returns.

For a more detailed diagnostic analysis of the model we examine Poisson standardized residuals,

$$e = \frac{R - E(R)}{\{E(R)\}^{1/2}},$$

which are plotted in Figures 10-12 in the **Appendix** for the three regions. The residuals tend to be large, which indicates Poisson overdispersion in the data, but otherwise no systematic discrepancies are apparent. The estimate of $\hat{\sigma} \approx 2$ also indicates Poisson overdispersion. Residuals are also plotted in Figure 13. This purpose of this figure is to assess the Poisson stochastic assumption. The residuals are fairly evenly scatter across the range of predicted values, and this suggest that the Poisson assumption is reasonable.

The confidence interval for Southern 3L exploitation rate in the second half of 1998 is quite large, and this deserves special attention. To address this we examine the exploitation and migration rate estimates obtained by constraining $\mu_{42} = 0.99$. The reason for doing this is to understand how such a large exploitation rate can be fairly consistent with the observed tag-returns, as measured using PQL. This is what the confidence interval suggests. The estimated migration and exploitation rates are presented in Figures 14-16. The model is taking most of the tagged fish out of Southern 3L, and moving them to Northern 3L and 3K, and to Placentia Bay. Hence, in the model the Southern 3L tag-returns are compared to a small tagged population, which leads to the high exploitation rate estimate. The problem is that the lack of tagging in some years, and the lack of fishing in 3KL during 1997, makes it difficult to reject this particular model. The predicted tag-returns are still fairly consistent with the observed tag-returns. We illustrate this in Figures 17 and 18 using the two examples we considered previously. The model predictions are reasonably close to the observations, and this is why the confidence interval is so large. Nonetheless, we feel this interval is an accurate description of the 1997-1998 tag-return information about Southern 3L exploitation.

5 Conclusions

Estimates indicate exploitation in Placentia Bay was 7% during January-June 15, 1997, and 4% in the remainder of the year. Exploitation was also very low during the first half of 1998 in Placentia Bay, but increased to 10% in the second half of the year. Exploitation in 3KL was very low in 1997 and the first half of 1998. Exploitation from the fishery in the second half of 1998 in 3KL was estimated to be 6% for cod in northern 3L and 3K, and 12% for cod in southern 3L; however, the Southern 3L estimate is quite uncertain.

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6 Appendix: Tables and Figures

Table 1. Summary of details for cod tagging experiments conducted in NAFO subdiv. 3Ps and Divs. 3KL during 1997-1998. PB - Placentia Bay, SMB - St. Mary's Bay, TB - Trinity Bay, BB - Bonavista Bay, EA - Eastern Avalon. HL - handline, TR - Trap, OT - Otter trawl.

DFO Stat. area	Year /no.	Location	Dates	Capture gear	Depth (m)	Number tagged	Mean length (cm)
3Psc	9701	Bar Haven, NW PB	9-12 Apr.	HL	48-60	996	62.1
	9702	Clattice Hbr., W PB	10 Apr.	HL	58-60	966	52.3
	9704	Bar Haven, NW PB	17-18 May	HL	50	817	65.0
	9705	St. Bride's, SE PB	25-28 May	HL	40	709	66.4
	9706	Oderin Bank, W PB	24-26 Jun.	HL	40	963	58.9
	9708	Lord's Cove, SW PB	25 Jun.-18 Jul.	TR/HL	18-40	793	53.5
	9715	Iona Islands, E PB	6-8 Nov.	HL	30-50	778	61.3
3Lq	9707	Riverhead, E SMB	25-26 Jun.	TR	16	701	56.9
	9714	Colinet Is., SMB	10-14 Oct.	OT	50	618	53.8
3Lj	9711	Ferryland, EA	30 July, 13 Aug	TR	25	88	62.2
	9713	Pouch Cove, EA	5 Aug 97	TR	25	220	56.9
3Lb	9703	NW Arm, TB	1-5 May	HL	40	788	56.2
3La	9709	Plate Cove, BB	9-10 July	HL	22	464	53.2
	9710	Open Hall, BB	12 June	HL	13	314	61.8
3Ki	9712	off Aspen Cove	23-24 July	HL	40	260	51.9
3Psc	9803	Bar Haven, NW PB	22-25 April	HL	21-50	2073	61.0
	9804	Paradise Sound, W PB	27-29 April	OT	151-206	1212	60.8
	9805	Wareham Rock, NW PB	May 1-3	HL	41-53	1037	61.9
	9808	Bar Haven, NW PB	19-24 Oct.	HL/OT	41-60	511	60.3
	9809	Eastern Channel, PB	17-22 Oct.	HL	52-80	883	58.8
3Ki	9807	South-east Fogo	18 June	TR	22	118	57.4

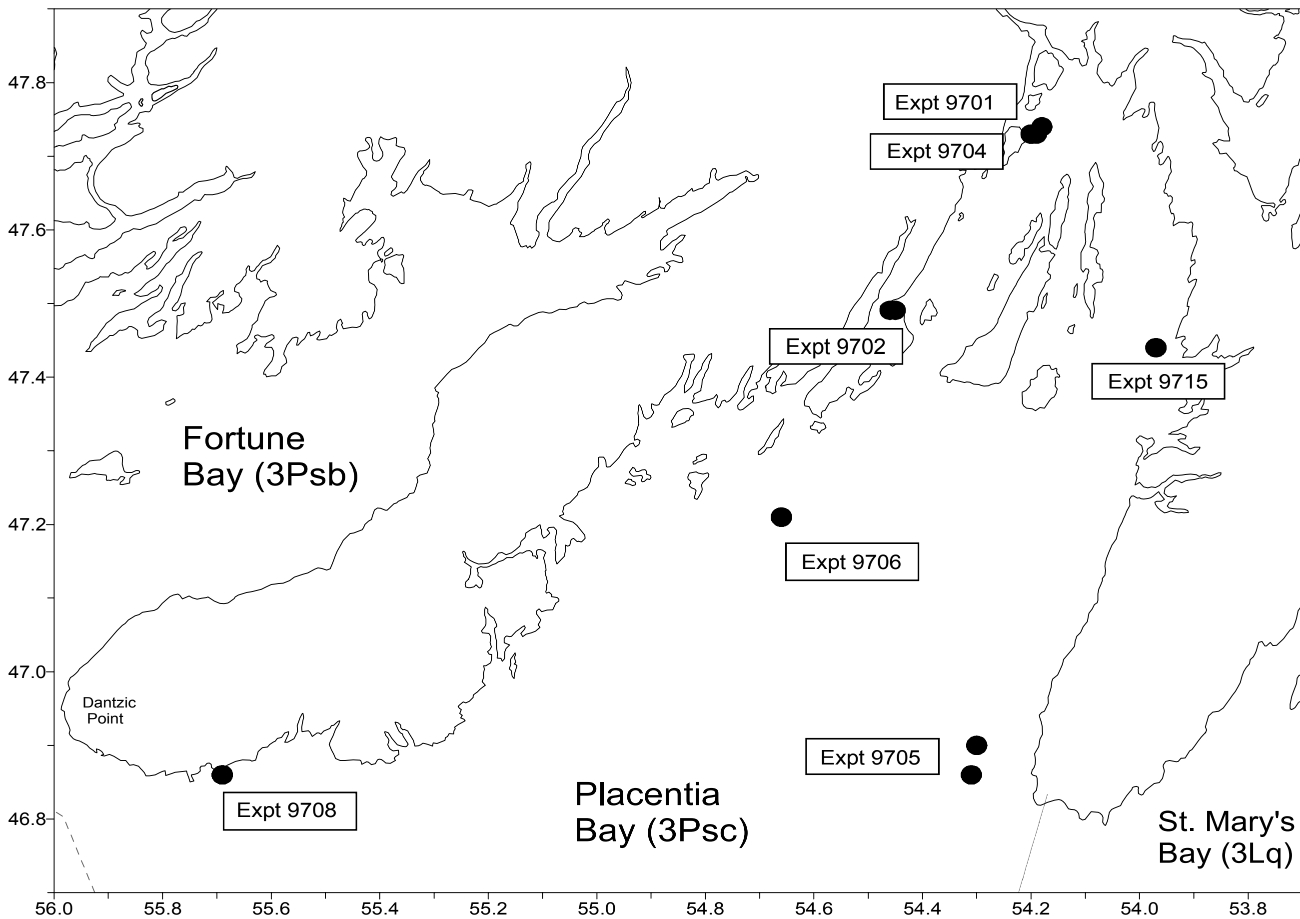

Figure 1a: Inshore sites where cod were tagged and released in 3Psc during 1997. See Table 1 for the details of each tagging experiment.

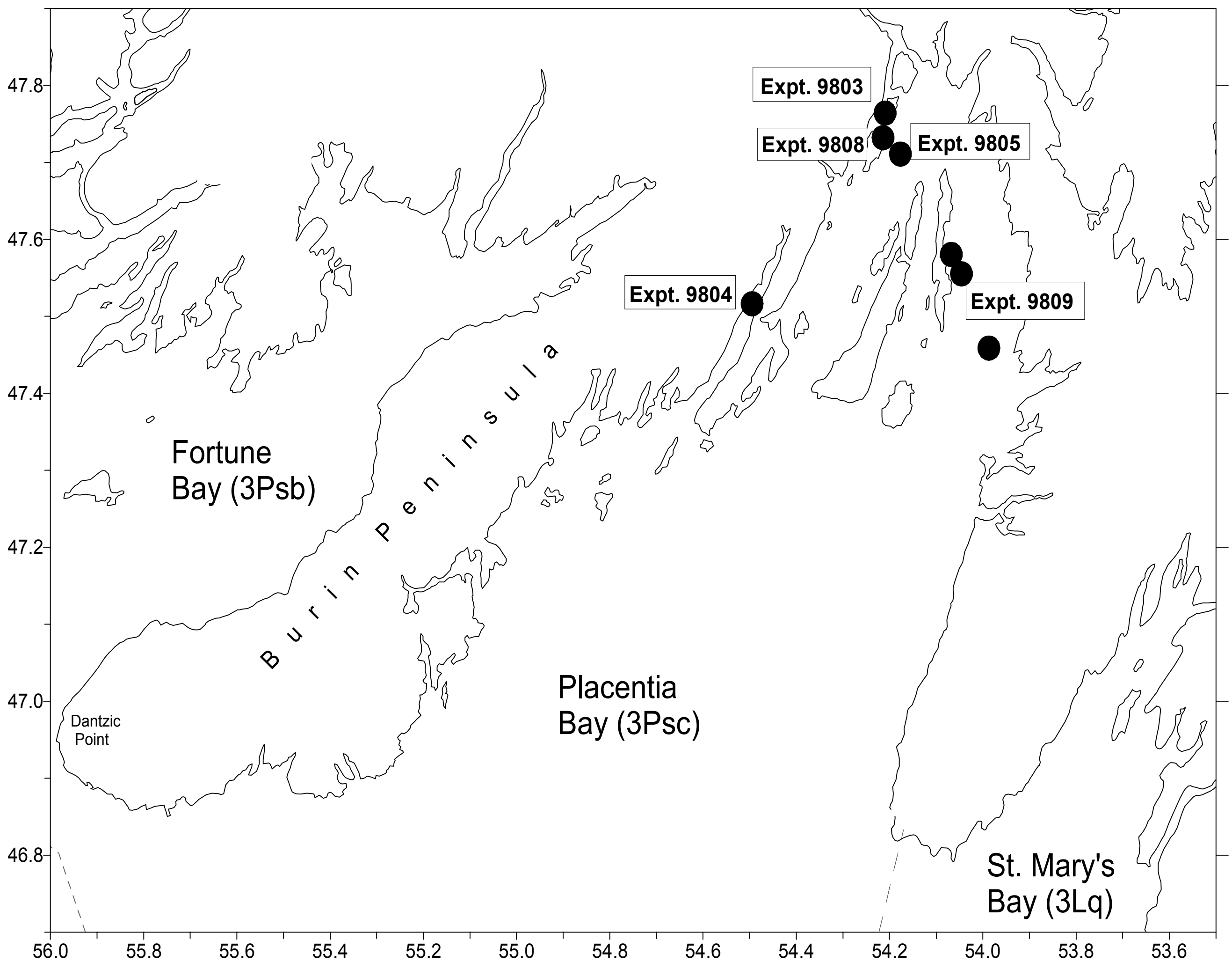

Figure 1b: Inshore sites where cod were tagged and released in 3Psc during 1998. See Table 1 for the details of each tagging experiment.

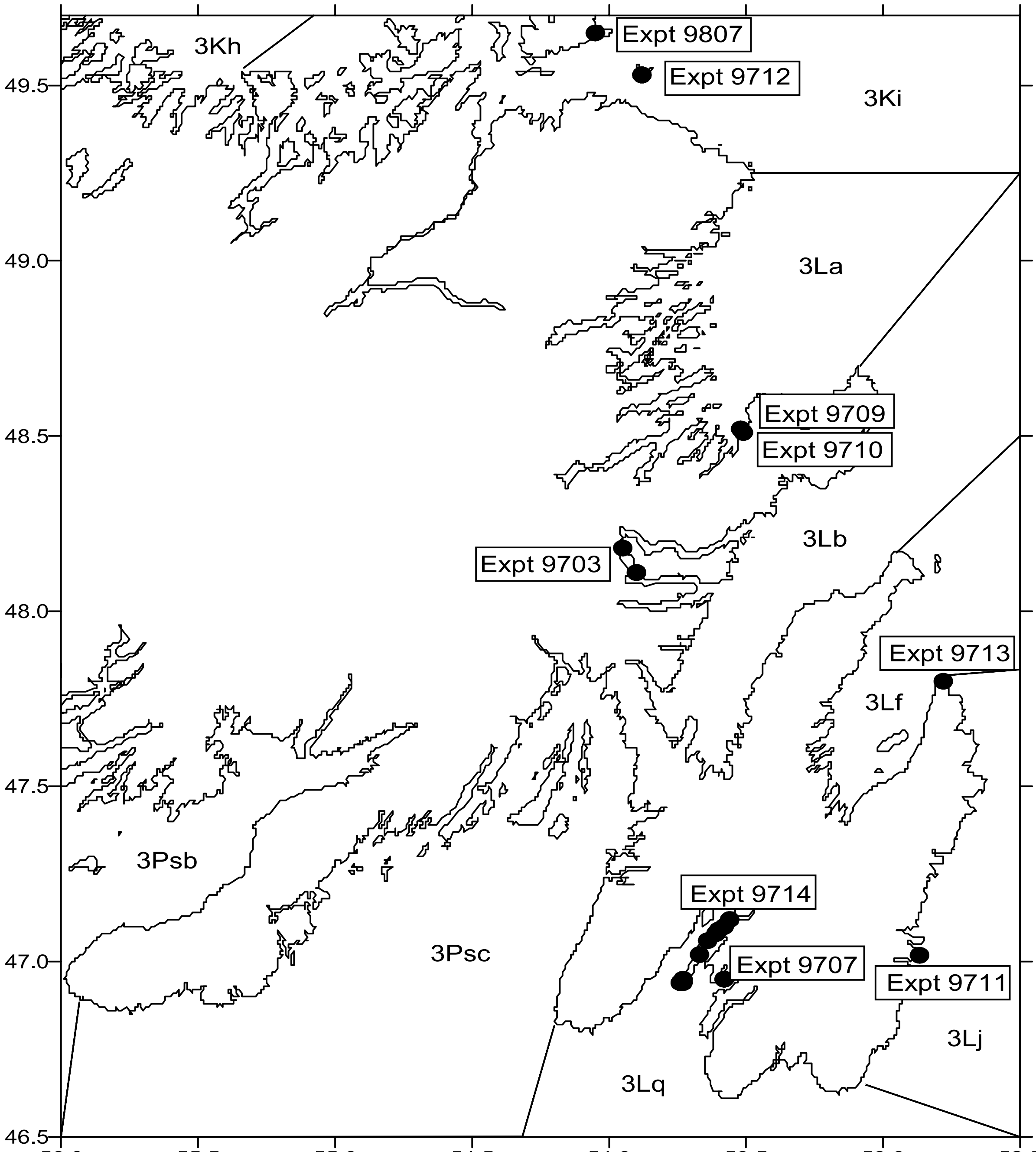

Figure 1c: Inshore sites where cod were tagged and released in 3KL during 1997 and 1998. See Table 1 for the details of each tagging experiment.

	Jan - Jun 15 1997	Jun 16 - Dec 1997	Jan - Jun 15 1998	Jun 16 - Dec 1998
Northern 3L and 3K	1102	724	0	118
Southern 3L	0	1627	0	0
Placentia Bay	3488	2541	4322	1468

Figure 2: Total number of tagged cod released, for all tag types.

	Jan-Jun 15 1997	Jun16 -Dec 1997	Jan- Jun 15 1998	Jun16 -Dec 1998
Northern 3L and 3K	122.7	266.2	65.0	3233.1
Southern 3L	18.2	97.3	57.0	851.0
Placentia Bay	2008.1	2935.3	67.7	7010.9

Figure 3: Reported catch (in tonnes) of the commercial, index, food, and sentinel fisheries in Placentia Bay and 3KL.

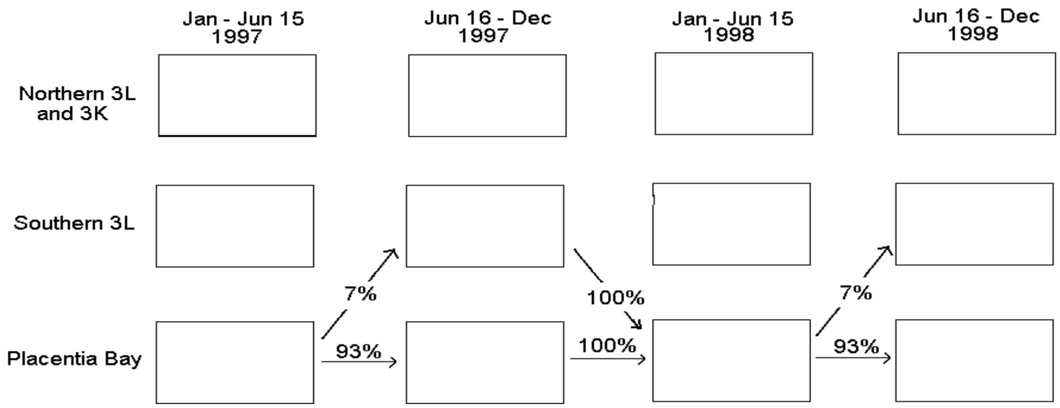

Figure 4: Migration route and estimated migration rates of fish tagged in Placentia Bay. All fish are assumed to return to Placentia Bay by the end of each year, and no migration is assumed to occur in the second half of each year.

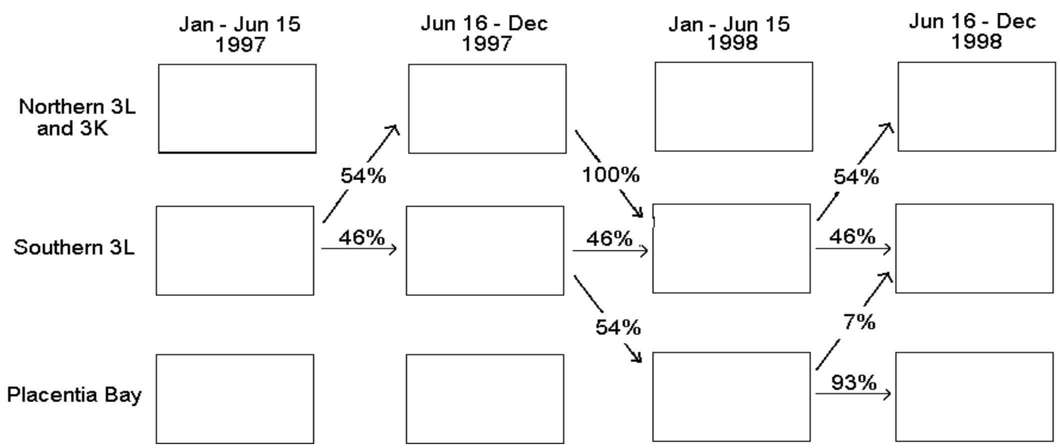

Figure 5: Migration route and estimated migration rates of fish tagged in Southern 3L. All fish are assumed to return to Southern 3L from Northern 3L and 3K by the end of each year.

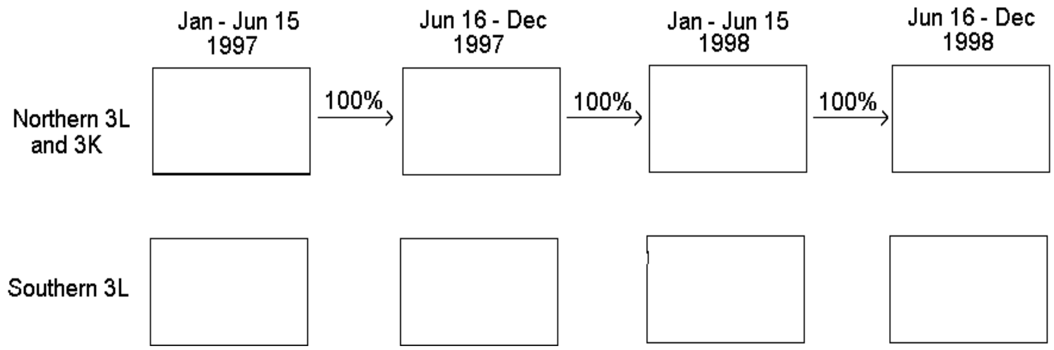

Figure 6: Migration route and assumed migration rates of fish tagged in Northern 3L and 3K.

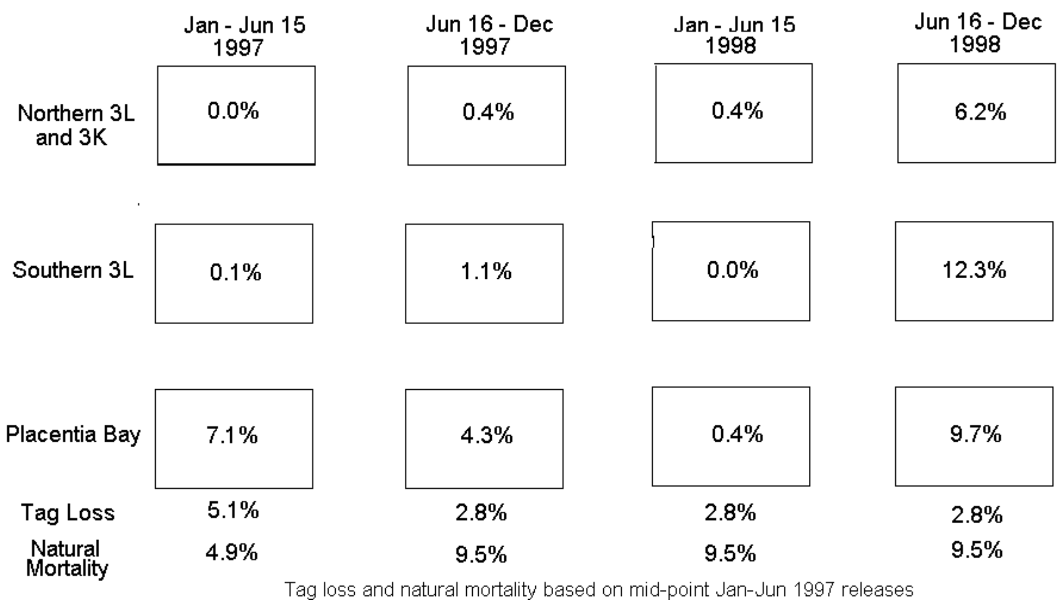

Figure 7: Exploitation rate estimates in Placentia Bay (3Psc) and the inshore regions of 3KL.

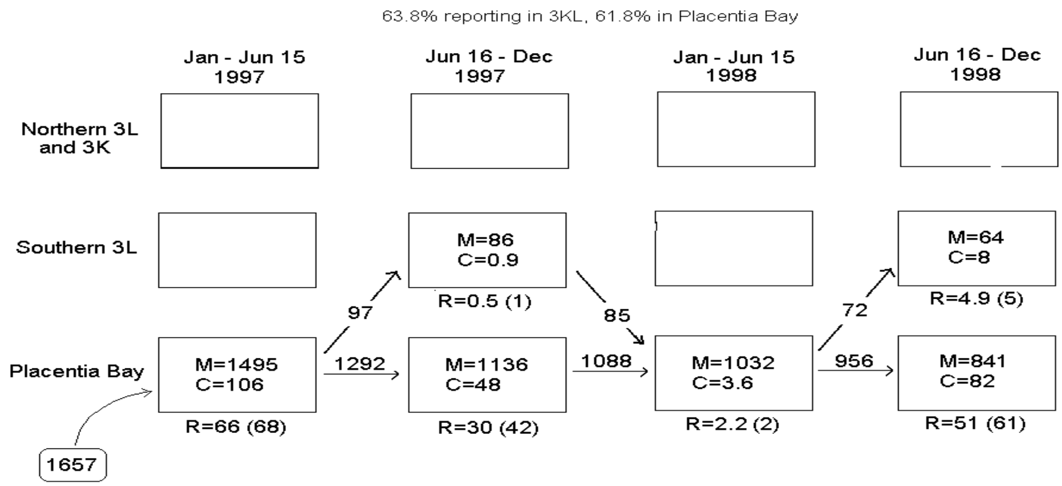

Figure 8: Migration model estimates of movements and catch from the 1997 release of single tagged fish in Placentia Bay. **M** is the number of tagged fish at the end of each time period, and **C** is the commercial catch of these tagged fish. **R** is the number of the caught tag that are reported. The number in parenthesis is the observed number of tag-returns.

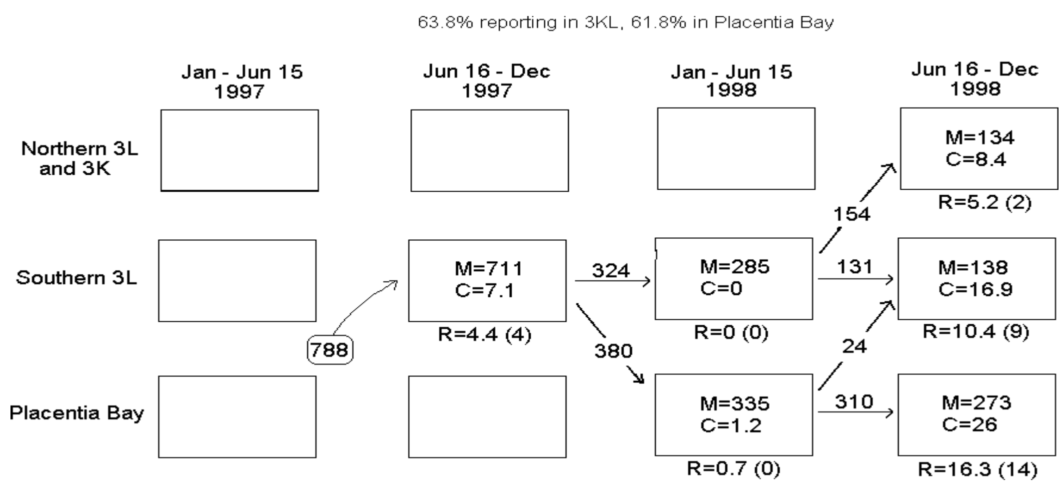

Figure 9: Migration model estimates of movements and catch from the 1997 release of single tagged fish in Southern 3L. **M** is the number of tagged fish at the end of each time period, and **C** is the commercial catch of these tagged fish. **R** is the number of the caught tag that are reported. The number in parenthesis is the observed number of tag-returns.

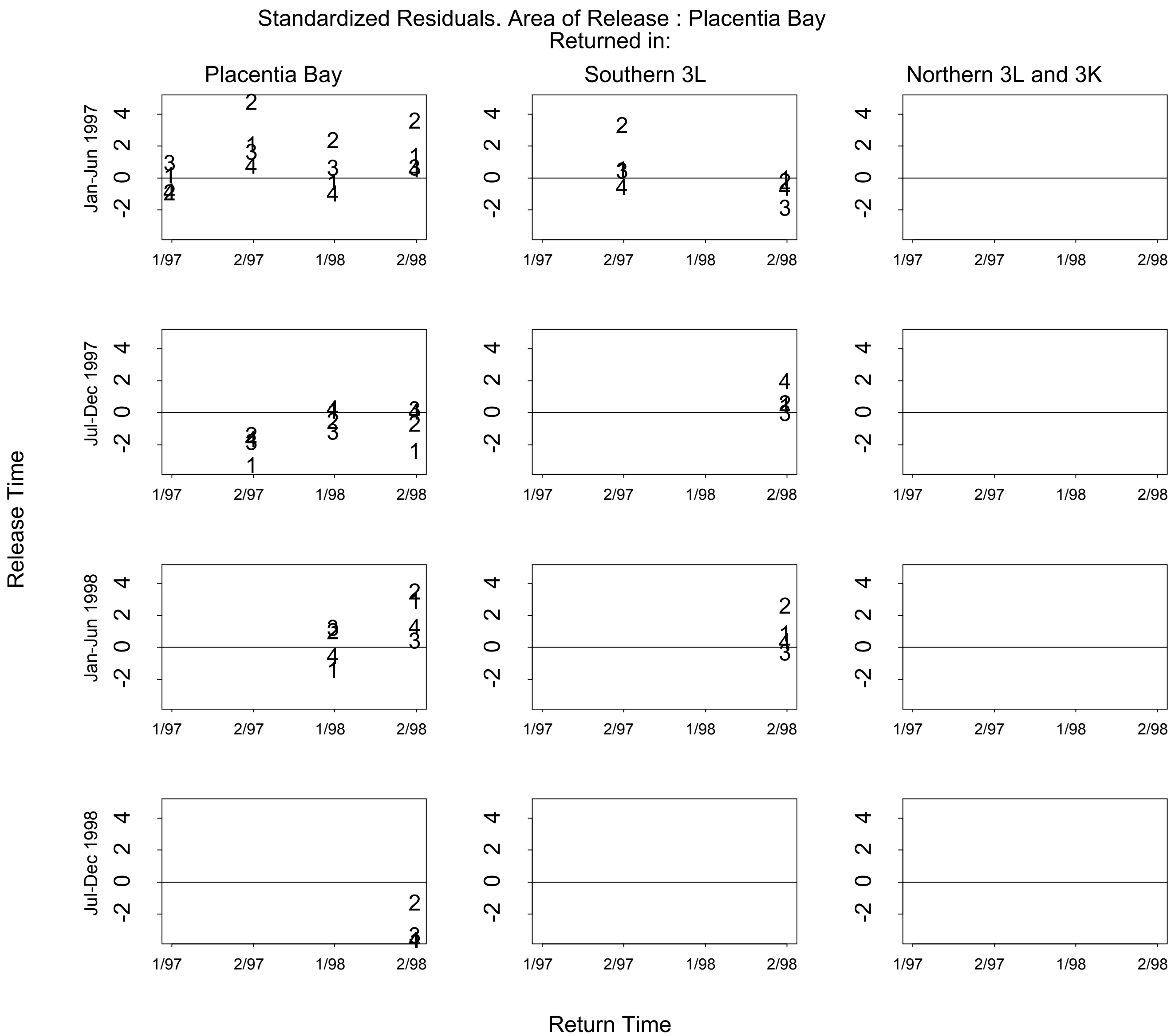

Figure 10: Poisson standardized residuals for Placentia Bay tag releases. Plotting symbols indicate tag type.

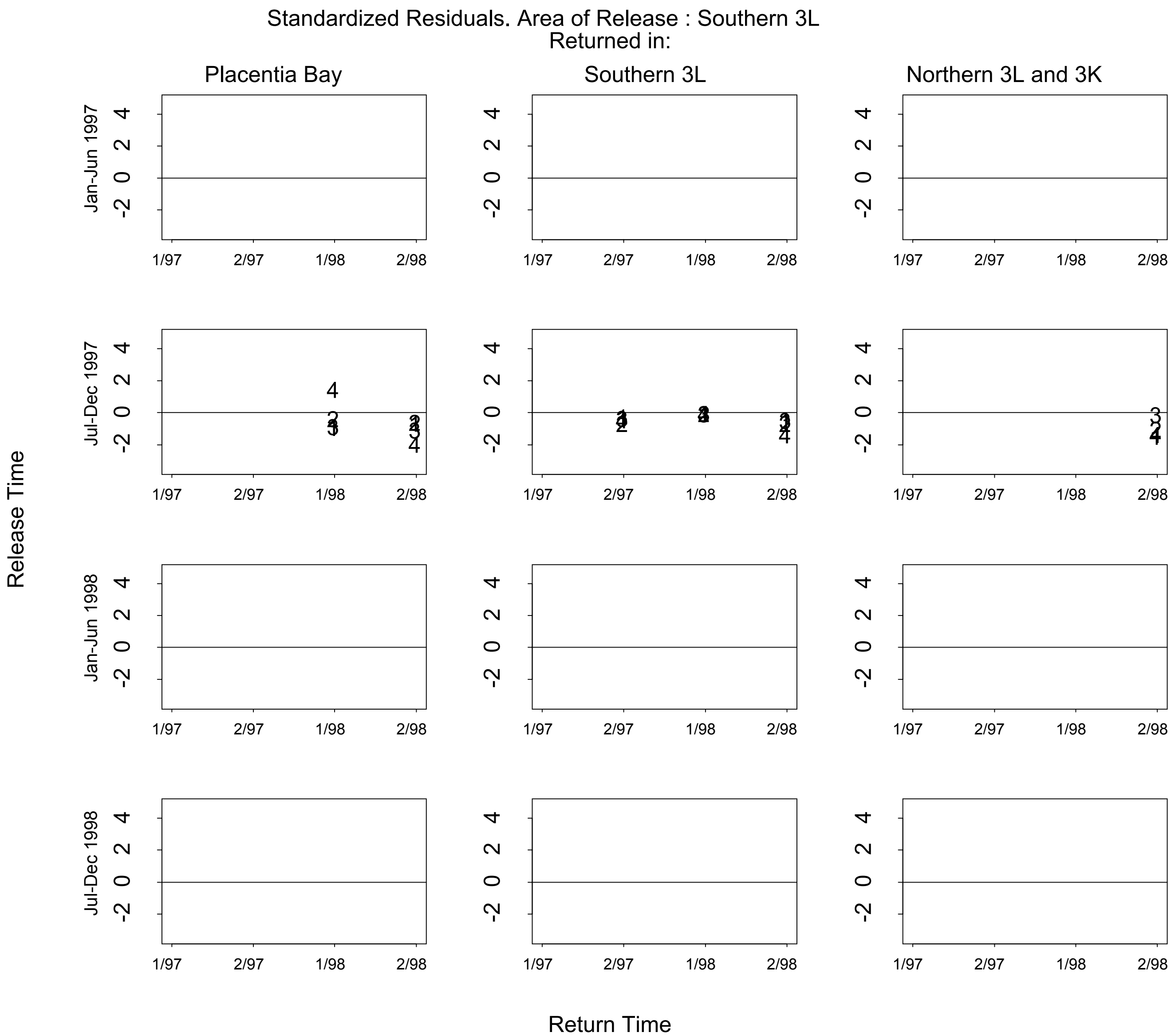

Figure 11: Poisson standardized residuals for Southern 3L tag releases. Plotting symbols indicate tag type.

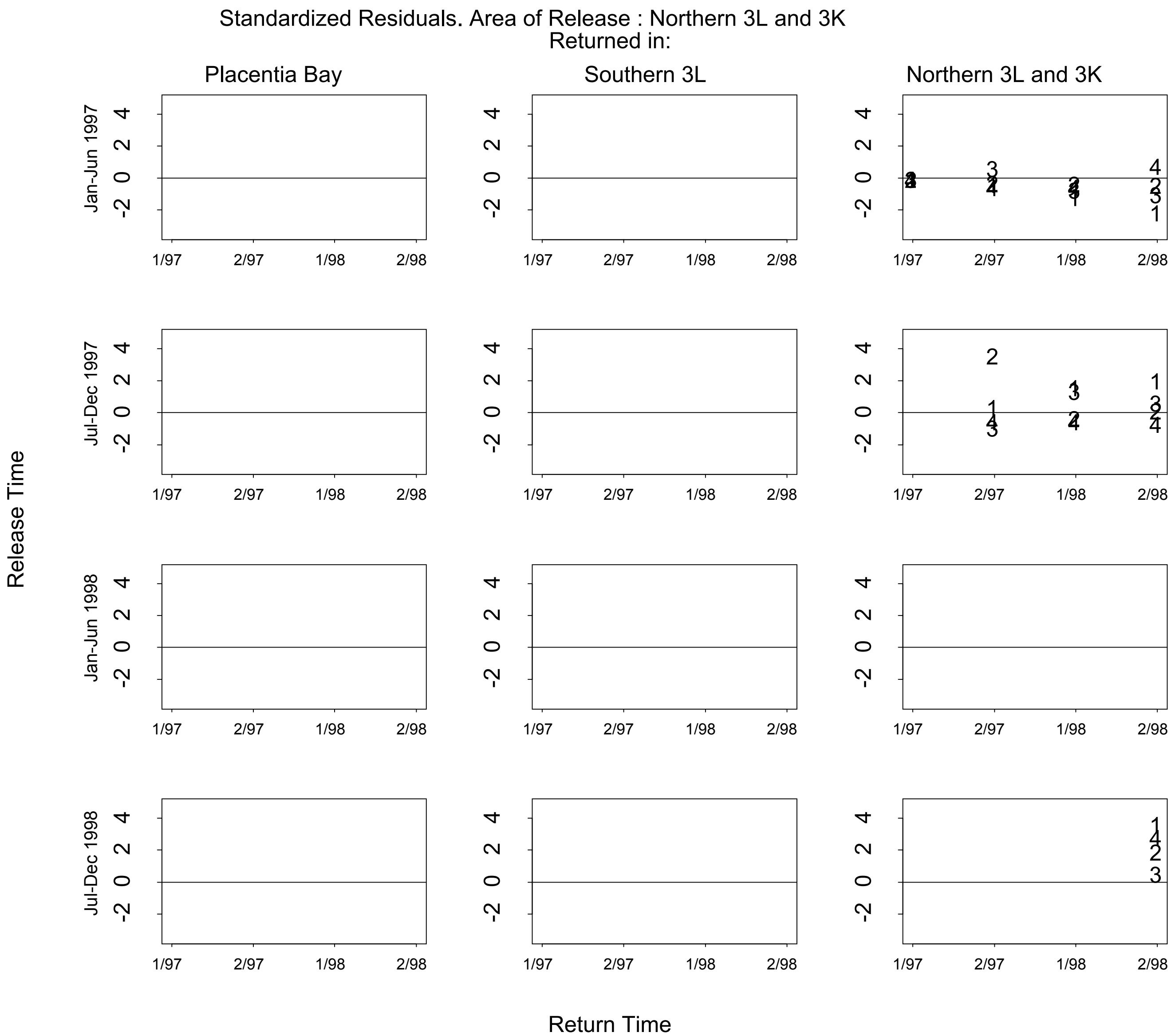

Figure 12: Poisson standardized residuals for Northern 3L and 3K tag releases. Plotting symbols indicate tag type.

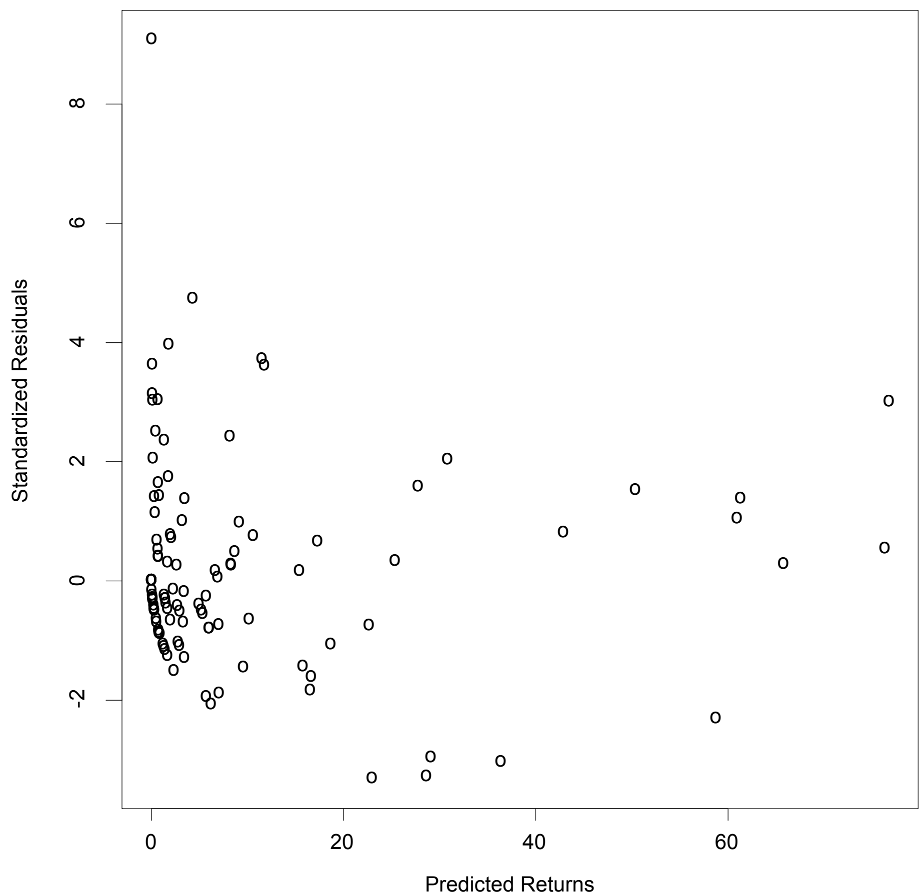

Figure 13: Standardized residual plot, versus predicted value for number of tag returns.

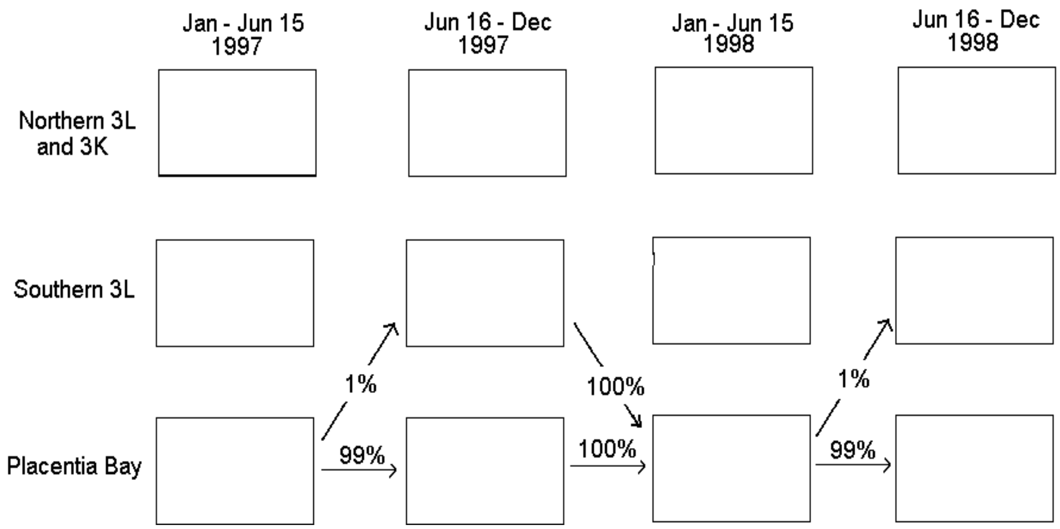

Figure 14: Illustrative migration route and estimated migration rates of fish tagged in Placentia Bay. All fish are assumed to return to Placentia Bay by the end of each year, and no migration is assumed to occur in the second half of each year. Estimates are based on assuming a 0.99 exploitation rate in Southern 3L during the latter half of 1998.

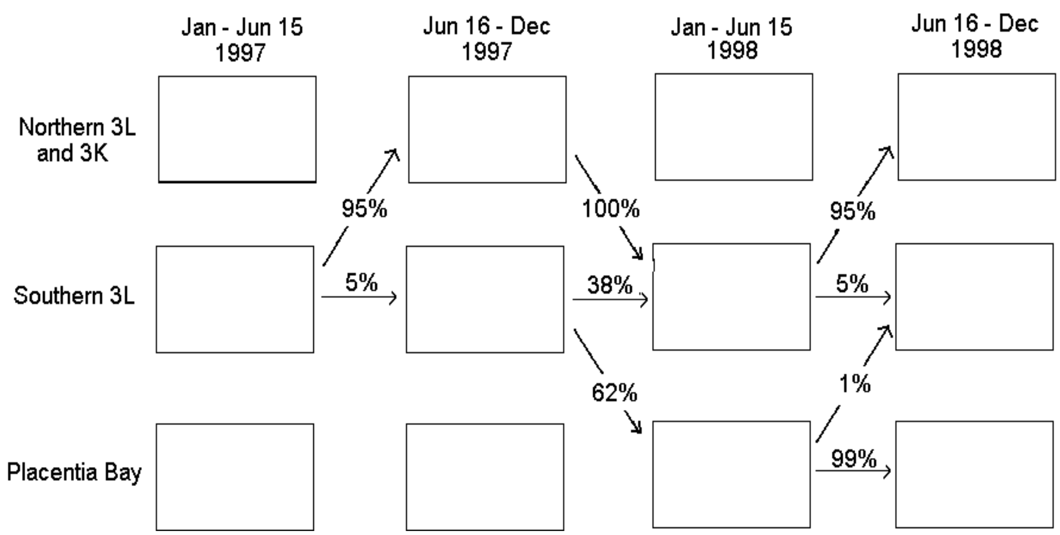

Figure 15: Illustrative migration route and estimated migration rates of fish tagged in Southern 3L. All fish are assumed to return to Southern 3L from Northern 3L and 3K by the end of each year. Estimates are based on assuming a 0.99 exploitation rate in Southern 3L during the latter half of 1998.

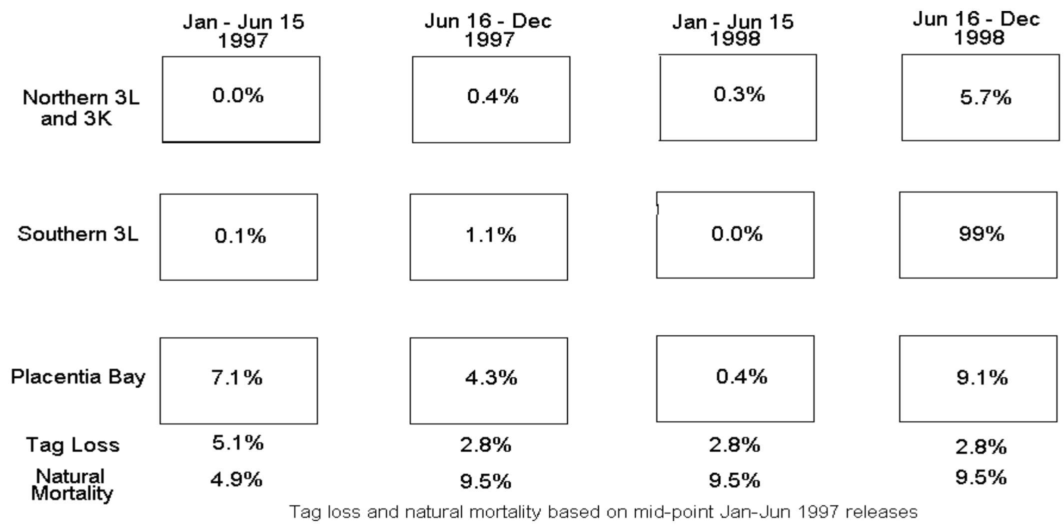

Figure 16: Illustrative exploitation rate estimates in Placentia Bay (3Psc) and the inshore regions of 3KL. Estimates are based on assuming a 0.99 exploitation rate in Southern 3L during the latter half of 1998.

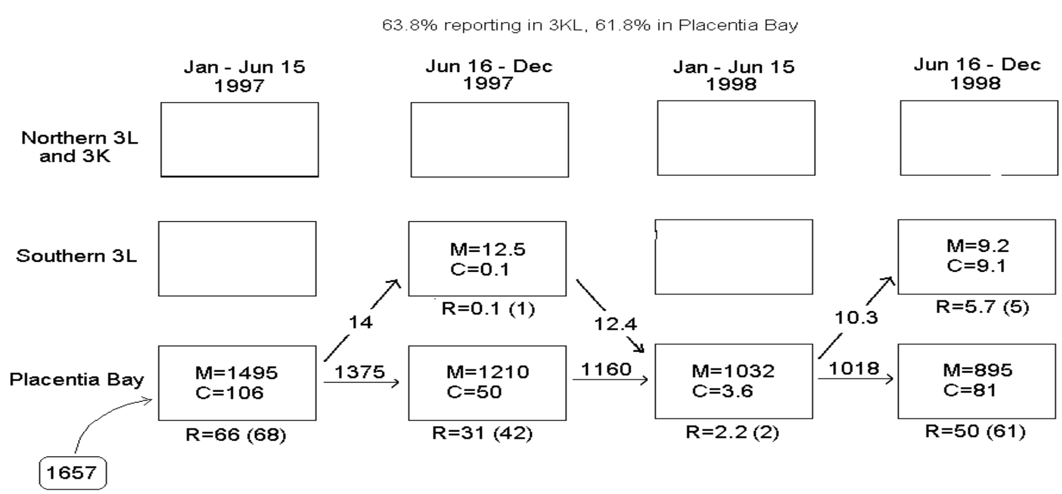

Figure 17: Illustrative migration model estimates of movements and catch from the 1997 release of single tagged fish in Placentia Bay. **M** is the number of tagged fish at the end of each time period, and **C** is the commercial catch of these tagged fish. **R** is the number of the caught tag that are reported. The number in parenthesis is the observed number of tag-returns. Estimates are based on assuming a 0.99 exploitation rate in Southern 3L during the latter half of 1998.

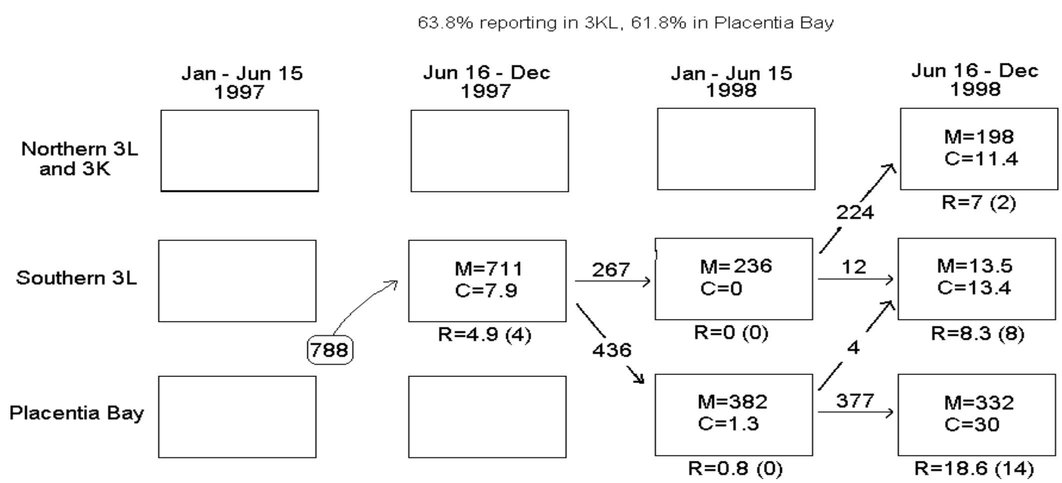

Figure 18: Illustrative migration model estimates of movements and catch from the 1997 release of single tagged fish in Southern 3L. **M** is the number of tagged fish at the end of each time period, and **C** is the commercial catch of these tagged fish. **R** is the number of the caught tag that are reported. The number in parenthesis is the observed number of tag-returns. Estimates are based on assuming a 0.99 exploitation rate in Southern 3L during the latter half of 1998.