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Université d'Ottawa • University of Ottawa



Thesis

Master's Programme in Systems Science

School of Graduate Studies

University of Ottawa

Spatial-Temporal Fish Stock Assessment

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©

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1. Introduction

At the present time the size of the fish stock for a given species over a large geographical area like the Canadian waters of the Northwestern Atlantic Ocean is estimated from annual catch statistics and independent research vessel surveys using seasonal aggregation methods. The standard stock assessment methodology used by fishery scientists around the world is called virtual population analysis (VPA) or a variant of it called cohort analysis. In these minimizing least squares methods, the size of the fish population of a given age or cohort (by weight or number of fish) is calculated. An estimate of the total stock size is then determined by summing over all of the ages in the population.

The results of VPA stock estimates are used directly to set annual total allowable catch (TAC) limits for commercial marine fisheries. Typically, a standardized biological 'reference point' is adopted to determine the TAC as a fixed fraction of the total stock size estimate. The established TAC determines total stock catches over the entire fishing area throughout the full length of the season.

The aggregation and aging of annual catch statistics for VPA's does not take into account the spatial distribution of catches over all fishing grounds or the intraseasonal temporal dynamics of these catches. When fish harvesting is concentrated on well-defined and discrete fishing grounds (e.g. banks, coves, bays and inlets) there is always a risk that fishing intensity will affect different areas in different ways.

For example, for schooling species, extensive fishing concentrated on a small area may threaten an individual spawning group with extinction if fish from that group are the only ones present in the area. In cases where discrete subpopulations of the aggregate define themselves spatially, limits on the catch for a specific area over a specific time period during the year should be much more effective in preventing the loss of valuable genetic diversity where there is strong differentiation between the fish of different spawning groups in the species.

To this end, the population is considered not as a single group uniformly distributed across the entire larger geographical area nor as a series of cohorts of various ages, but as a series of spawning groups - each with its own distribution across smaller areas within the larger whole.

Year-over-year catch data can be used to track fish spatial migration patterns of the various spawning groups throughout the year. The migration of the various groups can be simulated and estimates in the form of probability distributions of sub-population abundance in different locations throughout the year can be calculated.

The fish stock can be looked at as a set of dynamic subsystems in different states of abundance throughout the course of the year; each state is defined by the location and magnitude of the subgroups or spawning groups of the entire population.

1.1 Thesis Plan

In this thesis, a model of the spatial-temporal approach and the methodology for estimating fish population dynamics under uncertainty through the use of a partially observable Markov chain will be developed. The method will be applied to data from the Scotia-Fundy herring fishery.

A literature review follows in which the development of the methods of virtual population analysis and spatial-temporal analysis is outlined. The methodology of the partially observable Markov chain as it will be applied to the analysis of fish stock is described. Model results and consequences for the regulation of the seasonal harvest are discussed in the final section of this proposal.

2. Literature Review

2.1 Population Abundance Analysis

The idea of “virtual populations” was first conceived by Derzhavin (1922) who deduced that the total catch of fish from a given year-class of a given stock is equal to the catch that year plus the catch from subsequent years minus all the fish not of that year-class. The populations are called virtual because they are measured in terms of the observed process - the catch - rather than the actual process - the population.

Fry (1949, 1957) coined the term “virtual population analysis” (VPA) to mean the estimation of the size of a single cohort or year-class by summing, backwards from the year of maximum life-span, all of the catches of fish which had originated in the same, given year. With catch data and the estimates of age composition of the population, he was also able to calculate the total exploitable stock of a base year without the assumption of negligible natural mortality. A lower bound for the population size and an upper bound on the exploitation rate of the fishery could then be calculated by performing the analysis for all possible ages.

Ricker (1948) first performed a sequential population analysis using the catch equation (2.1) of Baranov (1918) with estimates of natural and fishing mortality at the maximum age of a cohort.

$$\frac{C_{i+1}}{N_{i+1}} = (1 - e^{-Z_{i+1}}) \cdot \frac{F_{i+1}}{Z_{i+1}} \quad (2.1)$$

where

C_{i+1} = catch of oldest year - class in year $i + 1$, N_{i+1} = population size of oldest cohort in year $i + 1$,
 $Z_{i+1} = F_{i+1} + M_{i+1}$, total mortality rate due to natural causes (M) and fish harvest (F) in year $i + 1$.

Beverton and Holt(1957) assumed that any fishery could be described in terms of two parameters:

- 1) μ = mesh size, and
- 2) F = fishing mortality coefficient,

and that the gear possessed knife-edge selectivity, so that all fish older than some t_μ are caught if they encounter the gear and all younger fish escape.

For the species that they studied annual recruitment levels seemed to be relatively independent of density so that the abundance dynamics of the stock denoted by N could be described by the function

$$\frac{1}{N} \frac{dN}{dt} = \text{constant}, \quad (2.2)$$

therefore they deduced that

$$\frac{dN}{dt} = \begin{cases} -MN & \text{for } 0 < t < t_\mu \\ -(M+F)N & \text{for } t > t_\mu \end{cases} \quad (2.3)$$

where M = natural mortality rate.

If $N(0) = R$, recruitment, then

$$N(t) = \begin{cases} Re^{-Mt} & \text{for } 0 < t < t_\mu \\ Re^{-Mt_\mu} e^{-(M+F)(t-t_\mu)} & \text{for } t > t_\mu \end{cases} \quad (2.4)$$

Gulland (1965) showed that varying fish mortality by age could be determined by calculating backwards from older to younger fish. His model, however, can only be used for estimating rates of mortality of cohorts that are no longer part of the population. For practical purposes, values of natural mortality for cohorts still present in the fishery are necessary to calculate current population estimates.

Jones (1961, 1968) devised a calculation of F for cohorts still present in the population by using the ratio of catches from the year-class during two consecutive years to estimate the ratio of the stock size at the end of the year to the catch from that cohort during that year.

Cohort analysis, a modification of VPA, was developed by Pope (1972). Estimates of mortality are based on the ratio of population size estimates from the end of one year to the next. Values of fishing mortality can be calculated by subtracting the estimate of natural mortality.

Collie and Sissenwine(1983) developed a Delury (1947) model which had previously been modified by Allen (1966). It uses data from research vessel surveys to estimate population size via the catchability coefficient, q , which is assumed equal for all cohorts of fish.

$$P_{t,i} = qN_{t,i} \quad (2.5)$$

where $P_{t,i}$ is the survey abundance at time t of fish of age i .

Since

$$N_{t+1,i} = (N_{t,i} - C_{t,i})e^{-M} , \quad (2.6)$$

therefore

$$P_{t+1,i+1} = (P_{t,i} - qC_{t,i})e^{-M} + e_{t,i} , \quad (2.7)$$

where $e_{t,i}$ is the equation error. The equations are solved simultaneously for q by a non-linear least squares estimation procedure and then an estimate of population size by age can be computed by dividing each P_i by q . This method does not require aged data but assumes that q is constant so that estimates of population size by age will be biased but not the estimate of total population size.

At the present time, VPA is the most widely used method of fish size estimation because of the relative simplicity of the computational approach and because of the widespread validity of its basic underlying assumption of uniform distribution of a stock over its habitat. It is often true that even if a species is more heavily fished in some areas than in others, the fish population will eventually return to a uniform population density because of the dispersion of the fish throughout its habitat.

2.2 Spatial Population Analysis

Caddy(1970) did a survey of ocean scallops and noticed that they congregated in “patches” or were subject to “contagion”. Since scallops are basically sedentary creatures it is reasonable to assume that there will be little or no stock intermingling or movement by the stock of any significant distance. Caddy(1975) devised a method using spatial analysis where he analyzed the scallop population on the Georges Bank by dividing the scalloping grounds into areas of equal size and assumed that effort and population distributions were uniform only over these smaller localized areas.

Recently GIS (Geographical Information Systems) have been used to perform some marine analysis on a spatial basis but most of this work relates to oceanographic issues. There has been little work in this area with respect to fishery issues and stock assessment. Kulka (1990, 1995, 1996) has applied GIS to address the stock status of Northern Cod in NAFO divisions 2J3KL. In a recent paper, Hutchings (1996) examines the spatial dynamics of the 2J3KL Northern Cod stock in defending the hypothesis of overexploitation as the sole explanation for stock collapse.

In this thesis a spatial-temporal model will be applied to assess the abundance of the Scotia-Fundy herring stock complex in Atlantic Canada. The herring is a highly mobile species characterized by well-defined migratory patterns through its habitat and detectable differentiation among spawning stock groups and another so that the dynamic behaviour and control of the stocks can be analyzed spatially by geographical zone.

3. Methodology

The spatial-temporal behaviour of a stock of schooling fish such as herring can be regarded as a dynamic system which can be broken into discrete stock components (spawning groups) which are characterized by specific migration patterns. The states of the subsystem are defined by the location and abundance of the spawning group during its particular seasonal migration behaviour.

The abundance of the stock in each geographical zone is estimated by assigning qualitative levels of abundance to the stock, i.e. “fuzzy” abundance measures: zero, low, medium, medium-high and high. These measures may be said to correspond to fishermen’s observations and categorical descriptions of stock availability. The abundance level of the stock of age-aggregated adult fish, the spawning stock biomass which is susceptible to harvest and distributed across each zone in a given time period, describes the state of the system.

For spawning groups which migrate along relatively specific routes each season, the state of abundance of the system during a period in time depends on the state of the system in the previous period, i.e. knowledge of how many fish there were in each location previously provides useful information about the state of the system in the next period. A Markov chain is ideally suited for describing the probabilistic population dynamics of this kind of dynamic system behaviour.

The following defines the key notation of the partially observable Markov chain problem methodology (Lane 1989b) adopted for this thesis:

Let $k \in \{1, 2, \dots, 52\}$ denote the k^{th} week of the year, and let $z \in Z$ denote a geographical zone in the habitat of the fish with $|Z| = N_z$, the number of zones in the fishery.

X_k is a N_z -dimensional random variable whose components represent the population levels of the adult stock in the various zones at the end of the k th week, so $\{X_k\}$ describes the dynamics of the

“core process”, the changing population levels of the age-aggregated harvestable fish stock throughout the year.

Define $p_{ijk} = \Pr(X_k = j | X_{k-1} = i)$, the probability of moving from an abundance level vector of value i at the end of the $(k-1)$ th week to an abundance level vector of j at the end of the k th week, where i and j are vectors of length N_x , representing pairwise discretized levels of stock abundance across all zones. Then the probability transition matrices, P_k , describe the non-stationary (i.e. weekly varying) process of stock abundance spatial-temporal dynamics from zone to zone and week to week throughout the season.

Since the process which is the population dynamic of the fish stock is observable only partially through, for example, catch statistics or other fishing observations (i.e. sampled with error), an additional N_z -dimensional vector random variable, Y_k , is required to define the observation process, i.e. actual catch statistics by zone for week k . Its components have values which represent the discretized levels of the catch and other observations of stock abundance status.

$$\text{Let } q_{jlk}(z) = \Pr(Y_k = l | X_k = j), z \in Z, \quad (3.1)$$

define the state-to-observation function that describes observations as a function of the state of the core process, the true population level. The state-to-observation or “reliability” function may also be expressed more parsimoniously as a function of the observation and the actual state only, and independent of the week in which the observations occur. Accordingly we let $q_{jlk} = q_{jl}$ for all k . The stochastic matrices $Q_k(z)$ are also called signal or reliability matrices. They describe the distribution of observation probabilities possible for given levels of the actual state.

The sufficient statistic (Bertsekas 1976), π , is defined as

$$\pi_j(k) = \Pr(X_k = j | I_k), j \in N, \quad (3.2)$$

where $\pi_j(k)$ is the state variable of the system defining the interaction between the partially observed actual population size and the available information about it, $I_k = (Y_k, Y_{k-1}, \dots, Y_1)$.

Using Bayes' formula, $\pi_j(k+1)$ is defined by the transfer function T_k as

$$T_k(\pi|I)_j = \pi_j(k+1) = \frac{q_{j|k} \sum_i p_{ijk} \pi_i(k)}{\sum_{i,j} q_{j|k} p_{ijk} \pi_i(k)} \quad (3.3)$$

for state vector indices i,j and weekly periods $k \in \{1, 2, \dots, 52\}$. Let $\pi(0)$ ($= \pi(52)$ of the previous year) describe the initial probability distribution of the stock at the beginning of the year. The $\pi_j(0)$, the probabilities of initial abundance levels, are assumed to be known through historical estimates or from research survey data.

Equation (3.3) uses Bayes' Theorem and the Markovian dynamics of the core process to infer information about the true level of spawning stock abundance through the sufficient statistic. Since $\pi(k)$ is the probability distribution of the population abundance levels, the population abundance can also be computed in each period by zone as an expectation and then summed over all zones to obtain total aggregate abundance. Estimates of abundance are updated for each period k .

There is one major caveat with the above rationale. No fishing effort implies no catch and consequently no additional information as to stock size whereas a catch of no fish when there has been effort expended provides considerable information about abundance. Consequently, equation (3.3) is used only for zone-week combinations where there is non-zero catch data or there is reason to expect that fishing effort took place.

To update population levels when there is no fishing, the following update equation, involving only the core process and the probability transition matrices, P_k , is used:

$$T_k(\pi)_j = \pi_j(k+1) = \frac{\sum_i \pi_i(k) p_{ijk}}{\sum_j \sum_i \pi_i(k) p_{ijk}} \quad (3.4)$$

The following section describes the application of this methodology to the Scotia-Fundy Herring fishery.

4. Application: The Scotia-Fundy Herring Fishery

The 4WX commercial herring fishery takes place along the Southern and Western Scotian shelf and into the Bay of Fundy (see map of fishing grounds in Appendix A). Within large herring stock complexes such as the Scotia-Fundy Atlantic herring stock, it has been found that there is a considerable degree of substock differentiation due to individual spawning groups which follow well-defined migration routes. For these substocks, there is relatively little interannual variability in terms of time or space migration (Stephenson, 1991) compared to many other commercial fin fish. In particular, the migration patterns of six spawning subgroups of the 4WX herring stock in the Bay of Fundy off Nova Scotia are relatively well-known (Stephenson et al, 1993). In addition, estimates of the total spawning stock size and proportions of spawning groups are available for this stock from annual VPA stock assessment estimates, e.g., see Stephenson et al. 1995.

In this thesis, the herring population is analyzed week-by-week during the year with respect to location and spawning group of origin. This is desirable in order that choices about fishing can be made which preserve the viability of all spawning substock components of the herring population.

Protection of genetic diversity and maintenance of individual spawning groups of the stock has been an important management consideration in this fishery for some time. The need for effective tools to further these goals has been exacerbated in recent years by apparent stock declines.

4.1 Determination of the probability transition matrices

Probability transition matrices, P_k , describe the process of stock abundance spatial-temporal dynamics from zone to zone and week to week. The matrices are determined by a construct that requires the following data:

- (1) an estimated range for the size of the whole stock,
- (2) estimated ranges of the relative proportions of each of the six spawning groups within the stock,
- (3) the migration patterns of the main wave of each spawning group within the stock,
- (4) the proportional run timing distribution of up to 5 'waves' of migration for each spawning group relative to the 'main' wave of migration.

The herring in a spawning group do not all move at exactly the same time. In this model each herring spawning group has been divided into 5 waves which move at successive intervals of 1 week duration. A 'main' wave may, for example, be accompanied by 'early', 'late', 'very early' and 'very late' runs of migrating herring for each spawning group.

The wave distributions have been modeled as one of five distribution possibilities: uniform, a large main wave with smaller waves before and afterwards, truncated uniform, and two skewed patterns which have a peak in distribution at one end of the migrating run. These distributions are depicted in Figure 1 below.

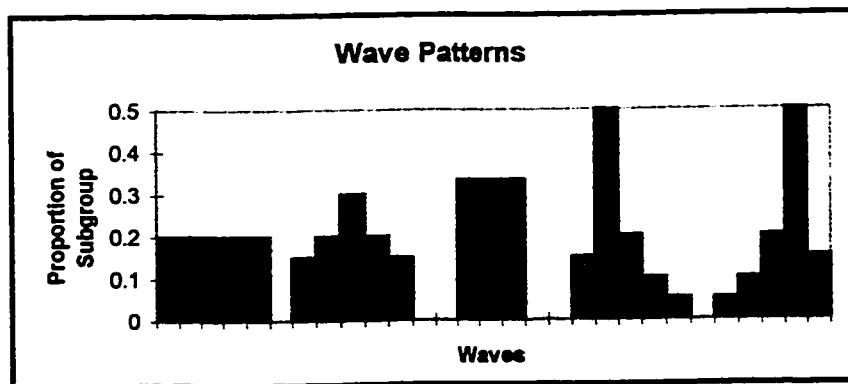


Figure 1. Spawning Group Run Timing Distribution Patterns

All component waves of the same spawning group are assumed to follow the same spatial migration pattern as the 'main' wave with associated delays and advances. The migration patterns are described in the incidence matrix (see Appendix B) of the system which describes the location of the main wave of each subgroup during each week of the year. For instance, the migration pattern of spawning group 1, which spawns in Scots Bay and overwinters near Chedabucto Bay, is as described in Table 1.

Estimation of the P_k proceeds by simulating the spawning group migrations from an initial estimate of the total herring stock. The initial size of the total herring population is randomized from a Normal distribution with mean 300 thousand metric tonnes and standard deviation of 100 thousand metric tonnes. The 95% range of this distribution (approximately ± 2 standard deviations or (100, 500) kilotonnes) covers the estimated historical aggregated stock size. Spawning group proportions are randomly determined to fall within estimated historical ranges for each spawning group. (See Appendix D - Spawning Group Relative Abundance Data.) Estimated sizes for component spawning groups are then simulated as a proportion of the simulated total and tracked along their respective migration patterns over time. The simulation model for estimating P_k is described in further detail below.

Weeks	Zone No.	Zone Name	Activity
1-6	9	Chedabucto Bay	Overwintering
7-17	12	Diffuse	Widespread, unavailable for harvest
18-27	2	Long Island	Pre-spawning, feeding aggregation
28	13	Yankee Bank	Feeding
29	10	N. B. Coastal	Feeding
30-32	8	Scots Bay	Spawning
33-48	12	Diffuse	Widespread, unavailable for harvest
49-52	9	Chedabucto Bay	Overwintering

Table 1. Migration Route of Spawning Group 1: Scots Bay (Chedabucto) (See also Appendix A map.)

Aggregate stock estimates for each spatially defined zone are determined by summing the incidence of the mixing among the waves of spawning groups in each zone during that week. At the end of each week, the population is reduced by estimated weekly natural mortality. (While harvesting fish certainly reduces local stock size, in this analysis it was not factored into the spatial-temporal adjustment to P matrices. Reduced stock size because of harvesting is reflected by the signals, through reduced catches.) The aggregated space-time stock estimates are then discretized into ten contiguous abundance levels for each zone.

State Level	1	2	3	4	
Fuzzy Definition	Zero	Extremely Low	Very Low	Low	Medium Low
Cell Definition	0	1-25000	25001-50000	50001-75000	75001-100000
Cell Midpoint	0	12500	37500	67500	87500
State Level	6	7	8	9	10
Fuzzy Definition	Medium	Medium High	High	Very High	Extremely High
Cell Definition	100001- 150000	150001-200000	200001- 250000	250001- 300000	300000+
Cell Midpoint	125000	175000	225000	275000	325000

Table 2. Population State Definitions (Tonnes)

Initially, discretized states defined 10 possible levels of age-aggregated harvestable adult stock abundance in each of 15 geographical zones for a total of 150 state space abundance level elements. Let $\{X_k\}$ denote the dynamic series of the changing population levels of the zones throughout the year. Therefore $|\{X_k\}| = (10)^{15}$ is the size of the total weekly state possibilities set. Enumeration of all possible states of the system by week would be very difficult; describing the period over period dynamics would be computationally intractable.

In order to deal with this problem of the curse of “dimensionality” the state representation must be greatly simplified. Firstly, we note that here are only a few spawning substocks of fish (6) in the stock complex. Secondly, often more than 1 subgroup of fish is in the same zone for the same week so that most zones are empty (for all intents and purposes) of appreciable amounts of migrating herring in any given week. Thirdly, many zones have fish in them for only a few weeks a year and these never attain high population levels (or attract high fishing effort).

Moreover, the spawning groups of fish move relatively independently of each other and their absolute sizes are also independent. Environmental carrying capacity constrains total stock size

but this acts equally on all groups. Finally, in all but a very few cases, fish move into a zone from at most two other, adjacent zones during a single weekly period.

For these reasons, the state dynamics of each zone are considered independently in this model. Instead of looking at the movement of the system as a whole from one state to another state described by the population level changes across all zones, we will simply look at the population dynamics within each zone over the weekly period.

The 52 week-over-week (nonstationary) transition matrices are estimated from the incidences of state-to-state change for the trials of the simulation. (Figure 2 describes the Pascal algorithm for calculating these matrices and the program code used is provided in Appendix E.)

When all trials have been run and population levels in each zone over each period recorded, the incidence matrix is examined. If there was movement by a wave of a subgroup from one zone with a given population level to another zone with a specified population level over that period, then there is said to have been a transition from the first population level-zone combination to the second. These transitions, for a given period, are counted over 500 trials and the ratio of that number to 500 is the transition rate from the first combination to the second combination. This matrix describing single period to period changes is 150×150 .

However, the probability transition matrix is designed to represent transitions between states of a single zone. The 10×10 diagonal blocks of the above 150×150 matrix are normalized to form new 10×10 matrices which represent the probability transition matrices for moving from an initial state to a final state within a single zone over a given period.

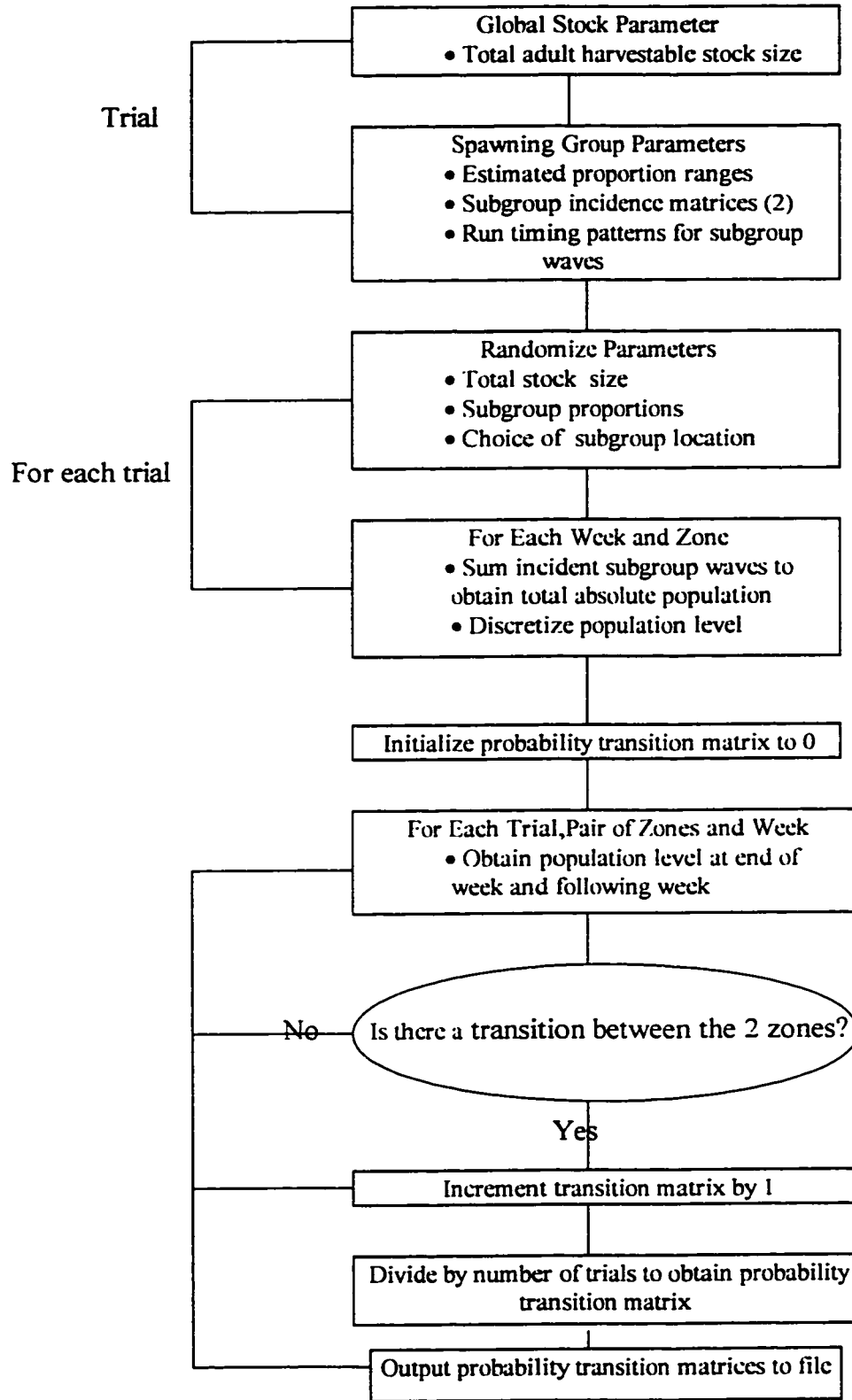


Figure 2. Flowchart for code to determine probability transition matrices.

During the sixth week, for instance, fish are moving from the 2 overwintering areas, Zone 1 and Zone 9, into the diffuse, non-geographical state known as Zone 12. The probability transition matrix for Zone 1 is as follows:

$$\begin{bmatrix} 1.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.727 & 0.273 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 1.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 \end{bmatrix}$$

The probability transition matrix for Zone 9 is:

$$\begin{bmatrix} 1.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.478 & 0.522 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.19 & 0.772 & 0.038 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.039 & 0.454 & 0.493 & 0.014 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.18 & 0.532 & 0.261 & 0.027 & 1.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 & 0.462 & 0.038 & 0.0 & 1.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.143 & 0.714 & 0.143 & 0.0 & 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 \end{bmatrix}$$

Since, in week 6, there are no fish in the other zones nor are there any fish entering them, the probability transition matrix for each of these zones is a 10 x 10 identity matrix.

4.2 Determination of the signal matrix:

The vast bulk (approximately 90% of the annual Total Allowable Catch) of the herring harvested in the 4WX fishery is caught by purse seiners. Catch data used in this analysis are restricted to harvests by this gear type of age-aggregated adult herring.

The seiner catch is discretized into levels of catch by zone and period. Varying weather conditions, the precise locations of fish and ships and fish behaviour all affect catch levels so that even with the same available stock of fish from which to catch and the same fishing effort there will be variability in the catch and therefore information from individual vessels fishing in the same zone about the abundance of the stock. As well, catch reporting is not without error.

The signal matrices are obtained from data about these catches over a year. The data are obtained from the vessel logbook reports of purse seiner captains. These data are compiled by the Department of Fisheries and Oceans Canada at the St. Andrews Biological Station. The use of these data in this thesis is acknowledged with thanks.

Catches from different zone-period combinations during the year provide a sample distribution of catch signals with respect to past reported levels of abundance. For instance the catch data for zone 9 during the 1991 season is as follows:

Week	Catch (metric tonnes)
1	800.0
2	985.2
3	745.0
4	2.0
5	275.0
6-43	0.0
44	980.1
45	4083.9
46	768.0
47	2069.0
48	2166.3
49	1181.9
50-52	0.0

Table 3. Chedabucto Bay (Zone9) Catch Data for 1991.

Since all of the fish except spawning group 2 (Scots Bay, Grand Manan) are present in Zone 9 during the overwintering period, during the first two weeks of the year and the last two weeks of the year, it will likely contain a population state of level 8 or 9 (i.e. between 200000 and 300000 tonnes) unless the year was very poor.

Using the catch data from 1991, catch observations in each zone are discretized with respect to the catch class to which the zone belongs. The zones are assigned to a catch class based on the magnitude of the catches in that zone. Appendix F contains the class to which each zone belongs and the catch states which are defined for each class. Catch state 1 denotes a catch of no fish for all zones. Catch state 2, for instance, denotes an expected catch of 250 tonnes for zones 6, 7, and

8 except during spawning periods, and it denotes an expected catch of 125 tonnes for zones 1, 2, 3, and 5 all year.

Each class has its own block signal matrix defined with respect to its catch histories and catch levels, and this whole matrix is contained in Appendix G. The resultant signal matrix section for Zone 9, representing the probability of a certain catch level (along the columns), given a population state level (along the rows) for all periods, is as follows:

State	Observation Level											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.0
2	0.53	0.1	0.13	0.1	0.06	0.03	0.01	0.01	0.01	0.01	0.01	0.0
3	0.2	0.1	0.24	0.2	0.1	0.1	0.01	0.01	0.01	0.01	0.01	0.01
4	0.15	0.1	0.2	0.22	0.15	0.11	0.02	0.01	0.01	0.01	0.01	0.01
5	0.1	0.1	0.18	0.2	0.15	0.15	0.07	0.01	0.01	0.01	0.01	0.01
6	0.1	0.1	0.1	0.2	0.2	0.14	0.05	0.04	0.04	0.01	0.01	0.01
7	0.1	0.1	0.1	0.12	0.18	0.2	0.07	0.05	0.04	0.02	0.01	0.01
8	0.05	0.05	0.06	0.1	0.12	0.15	0.1	0.11	0.1	0.07	0.06	0.03
9	0.05	0.05	0.05	0.05	0.1	0.1	0.15	0.1	0.1	0.1	0.1	0.05
10	0.05	0.03	0.03	0.05	0.1	0.1	0.1	0.12	0.12	0.1	0.1	0.1

The complete signal matrix for all zones is a collection of 6 matrices, each of 10 rows to correspond to the 10 possible population states in each zone, with the number of columns varying with the zone-class. Historical catch observation data by zone are discretized to form probability distributions for expected catch levels under (assumed) known abundance levels. These distributions form the zonal elements of the state-to-observation or signal matrix, Q. The complete set of Q matrices assigned to the zones is presented in Appendix G.

4.3 Initialization of the probability distribution:

The determination of the initial probability distributions on zone populations is straightforward. The initial probability distribution is a vector of 10 state elements for each of the 15 zones, or a 150 element vector in total. The first week of the year (i.e. the first week of January) is an overwintering period for the stock. This stock is assumed to overwinter in only two zones of its habitat, so that all other zones will have initial probability equal to 1.0 of having population level 1 (no fish).

For example, spawning group 2, which consists of herring which spawn in Scots Bay and overwinter off Grand Manan, comprises approximately 1.75 to 6.25 % of the total population in any given year. As a consequence, Grand Manan (Zone 1) has probability equal to 1.0 that its population lies within the second population state level (less than 25000 tonnes of fish) at the beginning of the first week of the year.

The remainder of the herring overwinter in Chedabucto Bay (Zone 9). As the total population is believed to have an approximate distribution of $N(300000,100000)$ tonnes, the initial probability distribution of the amount of fish in Zone 9 at the beginning of the year can be expressed as:

$$\Pr \{X_9 = 1\} = 0.0$$

$$\Pr \{X_9 = 2\} = 0.0$$

$$\Pr \{X_9 = 3\} = 0.001$$

$$\Pr \{X_9 = 4\} = 0.002$$

$$\Pr \{X_9 = 5\} = 0.003$$

$$\Pr \{X_9 = 6\} = 0.061$$

$$\Pr \{X_9 = 7\} = 0.092$$

$$\Pr \{X_9 = 8\} = 0.150$$

$$\Pr \{X_9 = 9\} = 0.191$$

$$\Pr \{X_9 = 10\} = 0.500$$

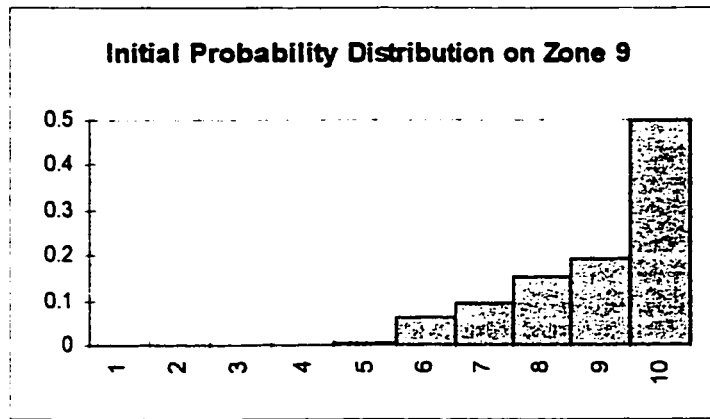


Figure 3. Initial Probability Distribution on Zone 9

The expected size of the spawning stock biomass for this initial probability distribution is therefore 272.925 thousand tonnes.

4.4 Determination of Catch Data to Test Model for Years 1991-1995.

An extensive database of catch data for each zone and week is available for this fishery from the logbook data series. Indeed, the federal Department of Fisheries and Oceans (DFO) has required the reporting of herring catch data on a daily basis by longitude and latitude location. However, during the early 1990's DFO Operations Branch redesigned its logbook statistical data sheet. The result compromised the collection of a separate dataset collected by DFO Science Branch on which the current research depends. The percentage of log reports for DFO on catches fell from 98% and 93% in 1991 and 1992, to 38% and 76% in 1993 and 1994 but returned to 100% in 1995.

Complete log data for each week and zone was available for 1991. For the years 1992 to 1994 monthly catch information by zone was described on maps (e.g. Fig. 11, Stephenson et al 1996). For this thesis these data were used to allocate catches to various weeks by inspection of the incidence matrix. In cases where the monthly total across zones did not sum to the fully reported monthly totals, zones were assigned increased catches according to where the fish were believed to be located. For 1995, full fishery weekly catch data by zone are once more available.

Catch data for 1991 indicated that the zones fell into several categories or classes with respect to magnitude of catch. The first class consists of Zones 6, 7, and 8, except for spawning periods in Zones 6 and 7 when catches seem to be higher than during the periods when fish are in pre-spawning feeding aggregations there. During spawning periods, Zones 6 and 7 are assigned to Q matrix class 5 (see Appendices F and G).

Class 2 Q matrices are assigned to Zones 1,2,3, and 5 where catches are relatively low all year. Class 3 consists of those zones for which the catches are lowest : Zones 10, 11 ,13, 14, and 15. Zone 9, the main overwintering area of Chedabucto Bay, is the only Zone in class 4. Despite the fact that Zone 9 contains almost all of the population during the winter, there are many weeks when there are no catches there since the herring are in Zone 9 for only a limited time period. However, there are also weeks of actual and potentially high catches.

Finally, Class 6 consists of only Zone 12. Zone 12 does not denote a zone as such but that state in which the fish are not available to harvesting gear since they are not schooling in large numbers but are spread out over a wide area. This passage in the seasonal migration pattern is referred to as the “diffuse” state of the stock prior to aggregation in pre-spawning feeding areas or in the spawning aggregations themselves.

In some years herring have been found in Zone 14 (Halifax) during the late winter/early spring. The herring may be moving southward through Zone 14 from the main overwintering area of Chedabucto Bay (Zone 9) towards the spawning areas, however at this time of year there is generally no fishing activity in Zone 14. Fish have been caught in Zone 14 at various times during the year but there is some dispute as to whether large schools found here are actually part of this fishery, or part of a separate inshore herring stock, or part of other offshore banks stocks. There are in-shore herring fisheries all along the Southern shore of Nova Scotia and there may also be some fish caught in Zone 14 which belong to fisheries farther off-shore. For these reasons, catch data from Zone 14 has been set to 0 for all weeks of the year from the assumption that Zone 14 herring do not belong to the normal 4WX herring stock.

Weekly catch data are converted from absolute numbers to discretized levels according to the observation sets of the Q matrices using the tables contained in Appendix F- Discretized Catch Data for Years 1991-1995.

5. Analysis

The goals of this research were twofold: to use current information about stock size to update stock estimates weekly within the season and to estimate sizes of individual spawning groups. First, a sensitivity analysis was undertaken to determine how sensitive the model updating scheme estimates might approach true stock size.

5.1 Sensitivity Analysis

The first analysis performed on the model was a sensitivity analysis. In order to verify how closely the model predicted total stock size, an initial actual stock size was set and weekly catches by zone were generated randomly according to the distributions contained in the signal matrix Q . The spatial-temporal updating method (3.4) was used to estimate expected total stock size in successive periods.

This was accomplished by first specifying zone population levels in each of the overwintering areas at the beginning of the year. Available information indicates that the area of Grand Manan (Zone 1) always has a small amount of fish during the winter which comprise the fish of spawning group 2, Scots Bay (Grand Manan). The population level in Zone 1 is set at 2 during the winter months. Depending on the assumed state of the rest of the fishery, Zone 9, Chedabucto Bay, has a population during the overwintering period which ranges from level 6 to 10. For each trial of the analysis, the initial population level of Zone 9 at the beginning of the year was set to a specific level, either 6 or 8 or 10, denoting “low”, “medium”, or “high” overall stock abundance.

As the herring migrate, they spread over a number of zones which varies with the time of year. The total “actual” population is then calculated as the sum of the populations in each zone where there are fish. Since population values have been discretized, these numbers are the midpoints of the state classes. Thus, this may cause the given total stock abundance to increase or decrease around the original fixed level. To compensate for this, the population levels in individual zones were adjusted upward or downward, without ever putting fish into a new zone or emptying a

populated zone, up to a maximum number of 6 times, in order to adjust the size of the stock for the beginning of the week to within 10% of the original fixed total stock size.

Weekly catch sizes in each zone were then generated randomly, according to the relevant distributions contained in Q, for each of the series of population state levels. Results from 10 trials with individual random number streams generated for each possible state of the fishery were used to compute average estimate and standard deviation measures for total stock size, compared to the input population size, thus giving an estimate of the accuracy of the updated population estimates. The results of the model sensitivity analysis are presented in Section 6.1 of this thesis and sample runs are presented in Appendix H.

5.2 Total Stock Size

In a second analysis, total stock size was estimated weekly for the years 1991-1995 using available catch observation data and updating equations (3.3) and (3.4). The results of the aggregate year-over-year estimates from the analysis are compared to the VPA stock assessment estimates for this stock. These results are presented in Section 6.2 of this thesis.

Since estimates for the winter months are generally lower than at other times, and proved to be more accurate in sensitivity trials of lower given population levels, averages and standard deviations were calculated on all yearly estimates as a group, and also on those estimates made during the first 4 weeks of the year grouped with the last 8 weeks of the year.

5.3 Spawning Group Size

The abundance status of the individual spawning groups is important for stock management. To estimate individual spawning group strength, population estimates were made of each spawning area during the spawning season using the update equation (3.3). A critical assumption was made that herring spend 3 weeks in the spawning area, regardless of when it arrives and leaves. Thus each fish would be counted exactly 3 times in the weekly population estimates and therefore the total strength was calculated as the sum of total weekly estimates on the spawning ground, divided by 3.

To calculate sample standard deviation of the abundance measure of the spawning groups of Trinity, Lurcher, Seal Island, and German Bank, it is noticed that, during the first week of spawning, the zone contains only the first wave of spawners. During week 2 the zone contains the first 2 waves of fish, during week 3 it contains the first 3 waves and during week 4 it contains the middle 3 waves of fish. Also, during week 5 it contains the last 3 waves of fish, during week 6

the zone contains the last 2 waves of fish, and the seventh week, only the last wave of fish are there. The sample variance of the estimate of spawning group size is, therefore, calculated as the average of the squares of the differences between the average and the sums of weeks: $1+4+7$, $2+5$, $3+6$.

Unlike the other spawning groups, the Scots Bay spawning group has been subdivided for the purposes of this model into 2 components. One part of the spawning group overwinters in Grand Manan and the other spends the winter in Chedabucto Bay. The fish coming from Grand Manan (Zone 1) seem to start spawning a week earlier than the fish coming from Chedabucto Bay (Zone 9).

If a_b denotes the a^{th} wave of subgroup b , then, during the first week of spawning in Scots Bay (Zone 8), it contains 1_2 . During week 2, Zone 8 contains 1_2 and 2_2 and 1_1 ; during week 3, zone 8 contains 1_2 and 2_2 and 1_1 and 2_1 , and so on. The sum of estimates for the population size of the Scots Bay zone for weeks 1 and 4 and 7 provides an estimate of the total spawning group size, as does the sum of estimates for weeks 2 and 5 and 8, as does the sum of estimates for weeks 3 and 6. Thus the sample variance is calculated as the sum of the squares of the difference between these sums and the average.

6. Results

6.1 Sensitivity Analysis

The sensitivity analysis was conducted to ascertain how sensitive the spawning stock estimates were with respect to true underlying abundance. Table 4, below, summarizes the results of the sensitivity analysis described in Section 5.1. (Detailed results are provided in Appendix H.) In summary, they are as follows:

	Input			Estimate	
	Average	Standard Deviation	Initial Model Estimate	Average	Standard Deviation
LOW (N=10 trials)					
All weeks of the year except 6-22	138	1	138	251	5
First 4, last 8 weeks of the year	139	2	138	228	19
MEDIUM (N=10 trials)					
All weeks of the year	237	1	238	265	5
First 4, last 8 weeks of the year	239	3	238	242	21
HIGH (N=10 trials)					
All weeks of the year	333	2	338	272	5
First 4, last 8 weeks of the year	337	5	338	251	21

Table 4. Data from sensitivity analysis.

(All data are in thousands of tonnes of total spawning stock biomass.)

Generally speaking, the estimates are lower during the winter months of the year when herring are congregated in only 2 overwintering zones. During much of the year, when fishing occurs and information updates are incorporated, the fish are spread out over a wide geographical area. When abundance is lower in a zone, the number of non-zero population states may be causing an unduly wide class size, and hence a larger population estimate as would be expected. If there were more population states, class width would be reduced and consequently estimated population might be closer to true population size which is taken at the midpoint of the class width.

Since population levels in individual zones are considered independently, the links between population levels in different zones are severed. Estimates in zones which are not fished become statistical averages without reference to the specific year in question. This causes the greatest problem in the early part of the year when the fish have left their overwintering areas and are feeding in a diffuse manner as they move towards the spawning areas.

When the herring are considered as being in "Zone 12" (beginning at approximately week 6) no observation signals are provided until fishing is again carried out starting in week 22. For this reason, all weekly estimates (based only on updating from P as in equation (3.4)) for weeks 8-22 were the same in each trial, regardless of seed or given population level. (Note that weekly estimates for the years 1993 and 1994 start to diverge from those of other years starting around week 18 rather than week 22. This is because fishing started early those summers, in week 17 and week 18, rather than week 22 as it did other years.). This is a smaller problem in the early fall when all of the main waves of all spawning groups are in Zone 12 for the weeks 43-44 but not all waves of all spawning groups are in Zone 12 at the same time.

While increased "input" population levels produced higher estimates than lower "input" population levels, average yearly estimates for population size did not vary greatly from given population level to given population level. Adjustments in values for the matrix Q yielded little improvement in the results.

Since the linkage between zones was lost when the definition of a state moved from that of the system as a whole to that of the individual zones, information about stock size from previous weeks was unavailable to improve subsequent estimates when fish left those zones with information and moved to new zones. Thus there was an information loss in this case.

6.2 Total Stock Size:

Estimates of total stock size were calculated as described in Section 5.2. (Appendix K contains the Pascal code used to obtain these estimates as well as the estimates for spawning area population.) Appendix J contains all weekly estimates of total stock size for the years 1991-1995. Yearly estimates of total stock size for each of the years 1991-1995 are summarized in Table 5:

Year	1991	1992	1993	1994	1995
Total Yearly Catch (tonnes)	88838	96415	92223	75593	56416
Estimates (thousand tonnes)					
Spatial-Temporal Methodology					
Average of All Weekly Estimates(except 6-22)	277	284	296	286	261
Standard Sample Deviation	38	55	64	60	33
Average of Estimates For Weeks 1-4, 45-52	233	232	242	225	216
Standard Sample Deviation (Weeks 1-4, 45-52)	21	29	27	24	26
Virtual Population Analysis Estimates	305	263	207	148	118

Table 5.
Comparison of estimates from Virtual Population Analysis and from Spatial-Temporal Analysis.

Decreased catches in 1993 are not reflected by a lower estimate of population size than in 1992. While total catch was lower in 1992 than in 1993, the catch was spread out over a longer time period. For instance, in weeks 45-52 of 1992 there were fish taken in Zone 1 only during week 45. In 1993, fish were harvested for 6 weeks near the end of the year in Zone 1. Likewise, in the spawning area of the one of the largest spawning groups, Seal Island (Zone 6), catches were made during 10 weeks in 1992 but during 15 weeks in 1993. Catches in the spawning area of the largest group, German Bank (Zone 7), were made during 12 weeks in both 1992 and 1993.

It is important to know when fishermen are actually fishing. If fishing is deferred at certain times of the year because of holidays or in order to conserve quota, it will have a significant impact on the estimates and must be taken into account.

In addition to the sensitivity analysis, 10 separate initial probability distributions were used as input to set estimated stock size at the beginning of 1991 to ascertain how fast this method converges. The first few weekly estimates produced are contained in Appendix I. All fish move to Zone 12 by the end of week 8, a zone which produces no signals. Since succeeding estimates are a statistical average of expected population, given the believed underlying distribution of total population, the estimates from all trials have converged after 7 weeks.

6.3 Spawning Group Size

Estimates of zone stock size during the spawning season were used to estimate the strengths of individual spawning groups as described in Section 5.3. The estimates of spawning group size (in thousands of tonnes) are shown graphically on the following two pages. They are as follows:

Year		Scots Bay	Trinity	Lurcher	Seal Island	German Bank	Total
1991	Average	53.77	63.75	27.9	66.2	154.1	365.7
	Sample Standard Deviation	8.128	5.536	6.247	16.29	3.14	20.27
1992	Average	77.61	53.78	27.9	95.05	133.9	388.2
	SSD	17.84	6.392	6.247	3.474	14.97	25.19
1993	Average	62.76	77.68	27.9	76.76	65.59	310.7
	SSD	12.71	8.643	6.247	23.14	5.642	29.02
1994	Average	80.07	54.6	27.9	52.89	157.7	373.1
	SSD	19.47	3.286	6.247	6.363	17.77	28.02
1995	Average	43.61	45.89	28.13	69.29	102.9	298.8
	SSD	7.489	5.348	6.295	14.78	18.14	25.92

Table 6. Estimates of absolute spawning group size.

In order to obtain separate estimates for the 2 components of the Scots Bay Spawning group (one of which spends the winter in Grand Manan, Zone 1, and the other, in Chedabucto Bay, Zone 9), data must also be used from the winter months when the components are not located together. An estimate of the size of the Grand Manan component may be made during the winter months since it is the only one located in and harvested in the Grand Manan area during the winter. While the Chedabucto component cannot be similarly estimated during the winter since it mixes with other herring at that time of the year, it is, of course, the difference in size between the summer estimates of population size in Scots Bay and the winter estimates in Grand Manan.

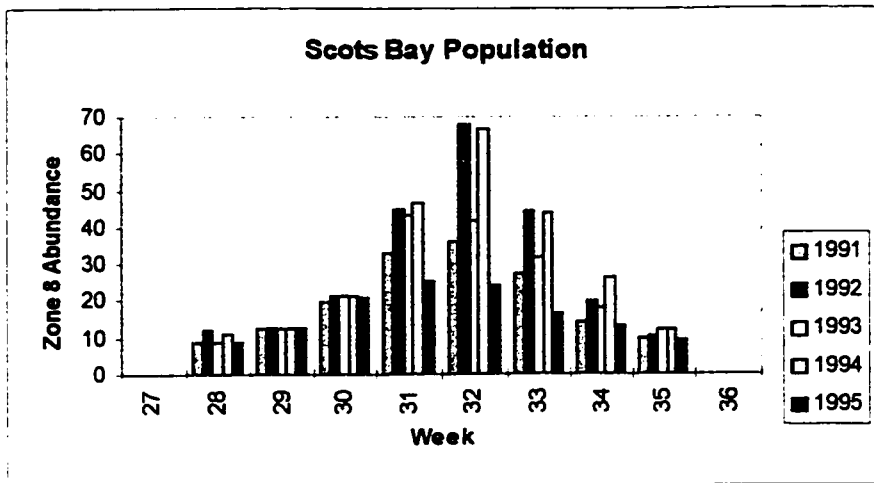


Figure 4. Weekly Population of Scots Bay (Zone 8) during spawning period

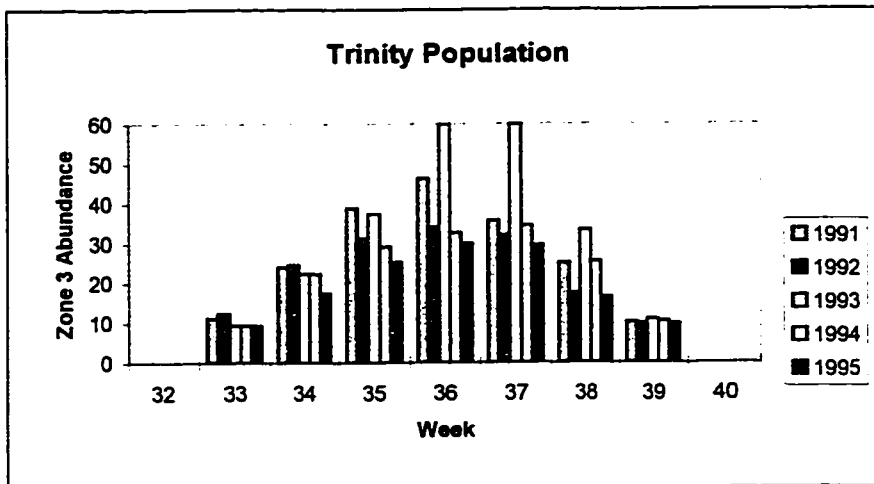


Figure 5. Weekly Population of Trinity (Zone 3) during spawning period

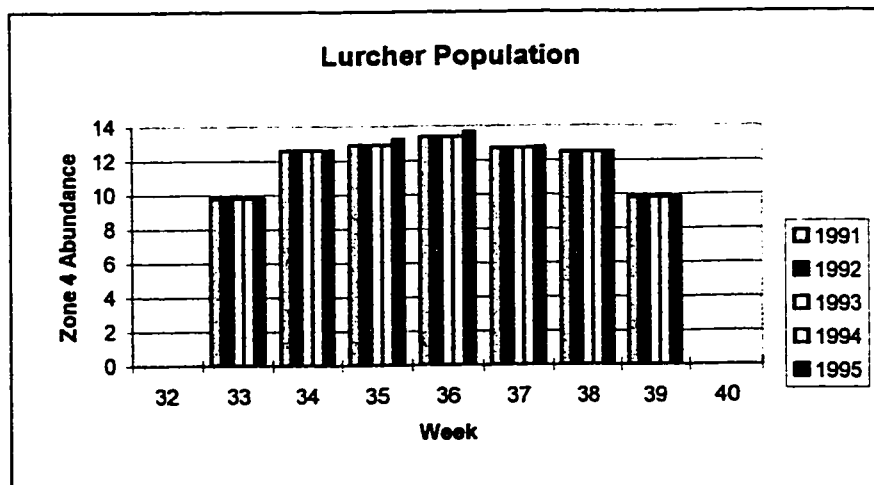


Figure 6. Weekly Population of Lurcher (Zone 4) during spawning period

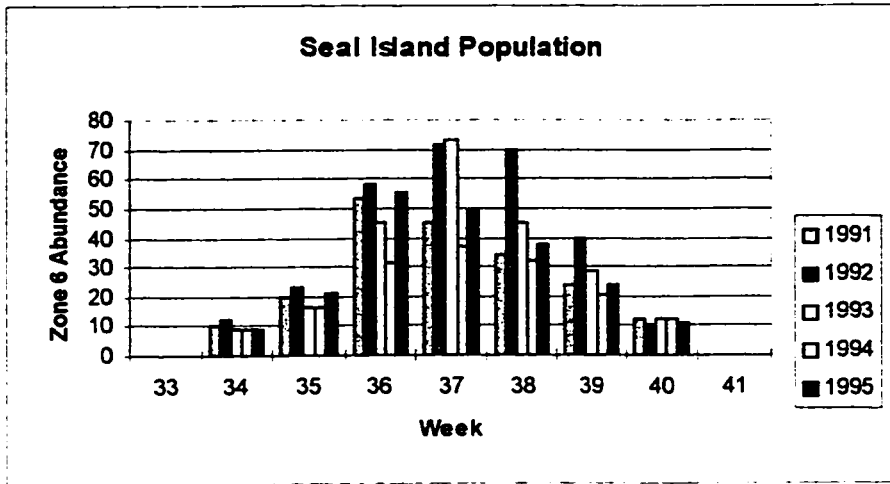


Figure 7. Weekly Population of Seal Island (Zone 6) during spawning period

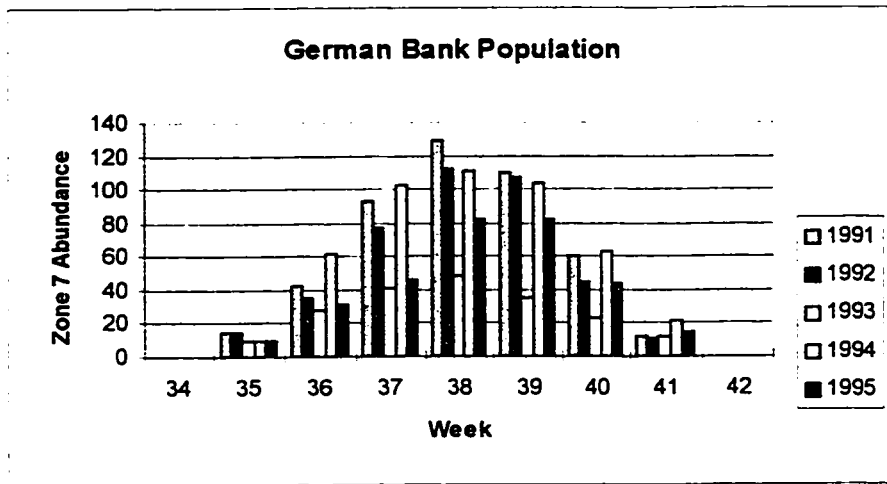


Figure 8. Weekly Population of German Bank (Zone 7) during spawning period

7. Conclusions and Extensions:

7.1 Conclusions:

During the harvest season for this fishery, spawning stock abundance estimates can be updated weekly by using current evidence of stock availability. Using the methodology of Section 3 and signals defined by absolute values of catch data discretized into catch levels, weekly estimates for individual zone populations were produced which were then aggregated to produce total spawning stock size estimates for the whole fishery.

In addition, estimates of the size of each spawning group during each year were made by using estimates of the zone populations of spawning areas during the respective spawning seasons. This information will enable fishermen to more accurately choose where and how much to fish in accordance with the goal of stock and spawning group conservation.

Probabilistic stock assessment can be performed for any fish stock which follows well-defined and well known migration patterns and for which full, current catch data by week and area is available. Cooperation among the various sectors of the fishery is required to obtain weekly spawning stock size estimates. In particular, obtaining the requisite data necessitates the willingness of fishermen to work with regulatory bodies and provide full, current catch data without delay.

In turn, fishermen can be provided with current information to help them with their decisions as to where and whether or not to fish. Since estimates of spawning stock abundance can be updated weekly, there will be multiple measures of (uncertain) estimates. Although individual fisherman might not be aware of a problem developing within an over-fished area, they can be given the information about it quickly and can change their fishing strategy accordingly.

Weekly estimates of abundance would facilitate the within season management of the fishery. The cooperation between fishermen and managers which is required to produce weekly

abundance estimates should lead to a better working relationship and fisheries which are more quickly responsive to current signals about the state and health of the fish stock.

7.2 Extensions:

The extensions of this work lie in two areas: application and methodology. Desirable extensions or modifications of the application of this model involve the generalization of signal data, changing the parameters of the system with respect to the underlying distribution of the size of the fishery, or migration routes of the constituent spawning groups, and the inclusion or exclusion of herring found off Halifax.

1. Catchability.

Catch data may provide biased information in that improved technology or the pelagic (schooling) nature of the fish stock can cause catches to increase even as population falls. There is some speculation that catchability may increase as population falls since a single school of a constant size would contain a higher proportion of the total number of fish as population falls. The signal matrix Q should be modified as more information becomes available about catches at different population levels.

In addition, if fishermen decide to change their fishing patterns during the year for reasons such as preserving quota, then this lack of effort will be reflected as negative information by the model which is false. It is important to identify those periods in which fishing effort occurs. This methodology could be generalized to signals which incorporate standardized information about stock size in cases where absolute values of catch are imperfect indicators, perhaps due to the imposition of TAC's, for instance, or an increase in the technological capability of the fishing fleet. Degree of effort, fishers' assessment of the abundance of fish and other ecosystem observations could also be incorporated into the definition of signals. An analysis of the qualitative information contained in the DFO Science Branch logbook dataset would yield much information in this regard.

2. Simulated Total Stock Size.

When the simulations were run to determine the probability transition matrices, it was assumed that this fishery has a total spawning stock biomass which is distributed normally with a mean of 300,000 tonnes and a standard deviation of 100,000 tonnes. If the fishery has shrunk significantly then these parameters should be changed in light of the new size as the P matrices which describe the core dynamic process of stock abundance could be affected.

3. Overwintering Zones.

Another major assumption that has been made is that the fish in the herring stock are located in only 2 different zones during the overwintering period. This is a simplification which may or may not be generally true.

During the winter months fish are caught in Chedabucto Bay and in Grand Manan as well as in two zones which are adjacent to Grand Manan. These catches in the adjacent zones may be misreported catches or the fish in this area may be more diffuse than expected. Overwintering herring have also been caught off Halifax (Zone 14) during this period. It is not yet known whether these are fish from the Scotia-Fundy herring spawning groups which may be taking a different migratory route or whether this is a new spawning group which should be included in this fishery. At present it has been assumed that these fish belong to a separate, perhaps inshore, herring stock.

If any of these scenarios are true or if the migratory route of any spawning group changes dramatically, then the incidence matrix used to generate the P matrices of the core process will have to be changed. While these changes are easily made to the model developed in this thesis, they will produce different output estimates.

4. State Space Definition.

The most serious problem with the present methodology lies in its state space definition. The assumption of independence of zonal populations with respect to each other was made because of the intractability of dealing with the state space of the system as a whole. In retrospect, it would

appear that a state definition which somehow considers the population of different zones jointly, say on at least a pairwise basis, would lead to improved accuracy.

If, for instance, herring are coming into a zone only from one other zone where the signals are indicating a particularly low level of herring, this restricts the possibility that the newly inhabited zone can reach certain population levels. As the model works at present, herring enter and exit the different zones of the habitat in unrelated ways because the zone populations are considered on an individual basis. This problem is especially acute when determining spawning group size as there is movement between many zones during spawning periods and the assumption of zone independence is particularly unreasonable at this time.

Spatial-Temporal Analysis is a new approach to producing estimates of stock abundance for a fishery which currently uses estimates produced by the Virtual Population Analysis methodology. The VPA estimates for the years 1991-1995 are initially higher than the Spatial-Temporal estimates but decrease more sharply over time. Yearly catch decreased by approximately 27% from 1991 to 1995 and this is reflected by a decrease in Spatial-Temporal estimates of total spawning stock size of approximately 14%, whereas the VPA estimates over the same time period decreased by more than 60 %. An examination of the degree of effort required to obtain these different catches (through total number of sets, for example) would clarify which of these estimates is more likely to be accurate.

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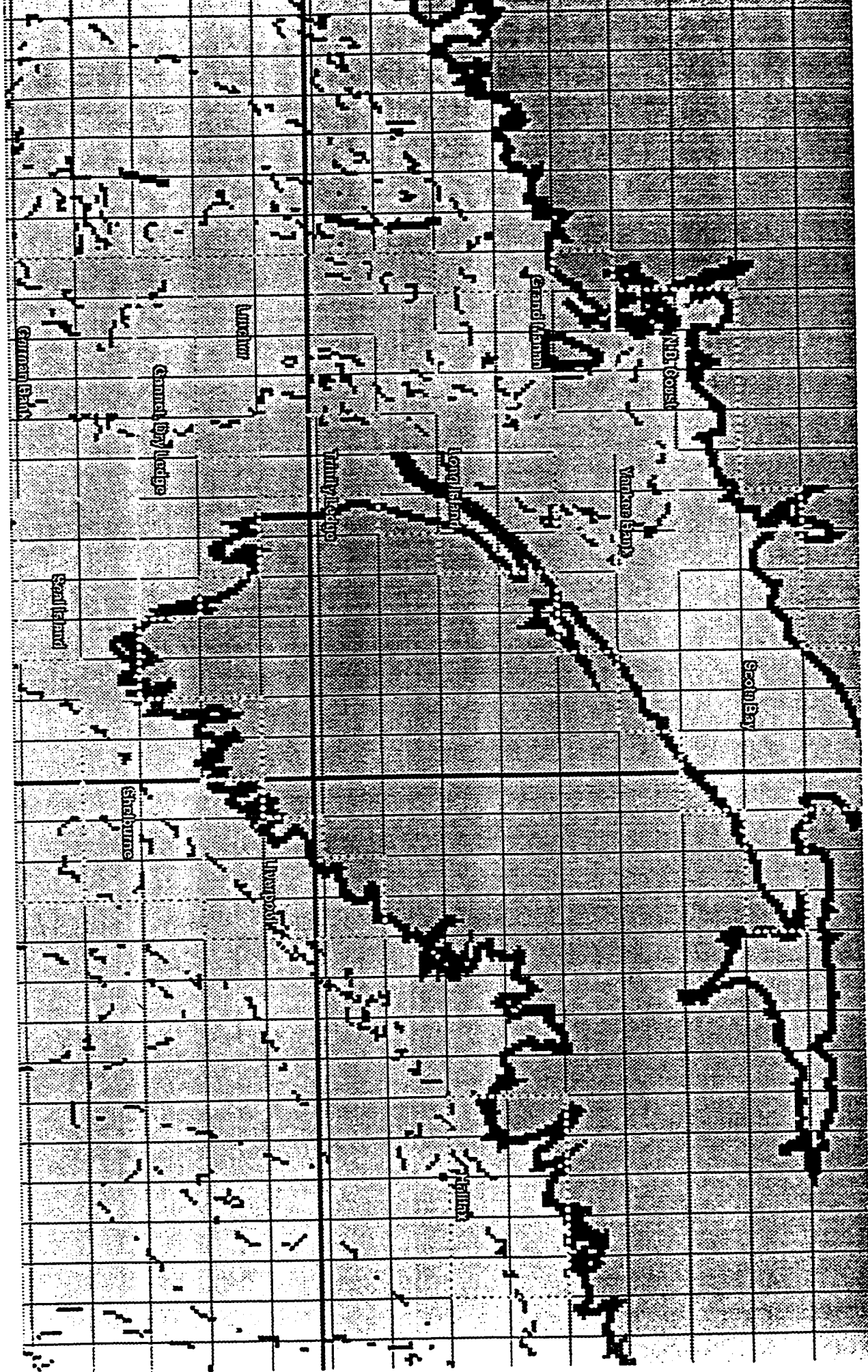
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Appendix A

Map of NAFO Division 4WX and the Scotia-Fundy herring grounds. Zones are denoted by name.
The key to zone numbering by name is contained in Appendix B.

Source: Map Info graphic.



Appendix B:

Table of herring fishery zones including geographic area description and zone numbers and names.

Zone Number	Name	Description
1	Grand Manan	Island off N.B. Shore
2	Long Island	Island off Western N.S.
3	Trinity	Fishing Ground South of Long Island, near N.S.Coast
4	Lurcher	Fishing Ground South of Trinity
5	Gannet, Dry Ledge	Fishing Ground South of Lurcher
6	Seal Island	Island off Southern Tip of N.S.
7	German Bank	Fishing Ground Southwest of N.S.
8	Scots Bay	Small Bay at Northern End of Bay of Fundy
9	Chedabucto	Fishing Ground Adjacent to East Coast of N.S. and Cape Breton
10	N.B. Coastal	Fishing Ground Along Coast of N.B.
11	Southwest Grounds	Fishing Ground South of N.S.
12	Diffuse	Fish are Feeding, Diffuse Throughout the Region
13	Yankee Bank	Fishing Ground Between N.S., N.B. (between Scots Bay, Grand Manan)
14	Halifax	Fishing Ground off Halifax Harbour
15	Liverpool	Fishing Ground Between Halifax, Seal Island

Appendix C

Spawning group zonal migration patterns by week. The following table provides the data on the main wave of each spawning group.

Spawning Group	No.	1	2	3	4	5	6
Month	Week	Scots Bay (Chedabucto)	Scots Bay (Grand Manan)	Trinity	Lurcher	Seal Island	German Bank
January	1	9	1	9	9	9	9
	2	9	1	9	9	9	9
	3	9	1	9	9	9	9
	4	9	1	9	9	9	9
February	5	9	1	12	12	12	12
	6	9	1	12	12	12	12
	7	12	12	12	12	12	12
	8	12	12	12	12	12	12
March	9	12	12	12	12	12	12
	10	12	12	12	12	12	12
	11	12	12	12	12	12	12
	12	12	12	12	12	12	12
	13	12	12	12	12	12	12
April	14	12	12	12	12	12	12
	15	12	12	12	12	12	12
	16	12	12	12	12	12	12
	17	12	12	12	12	12	12
May	18	2	12	11	11	11	11
	19	2	12	11	11	11	11
	20	2	2	11	11	11	11
	21	2	2	5/7	5/7	11	11
	22	2	2	5/7	5/7	11	11
June	23	2	2	5/7	5/7	11	11
	24	2	2	4/5	4/5	11	11
	25	2	1/2	4/5	4/5	11	11
	26	2	1	4/5	4/5	5	5/7

Spawning Group	No.	1	2	3	4	5	6
Month	Week	Scots Bay (Chedabucto)	Scots Bay (Grand Manan)	Trinity	Lurcher	Seal Island	German Bank
July	27	2	1	4	4	5	5/7
	28	2	13	4	4	5/6	5/7
	29	13	10	4	4	5/6	5/7
	30	10	8	2	2	5	5
August	31	8	8	2	2	5	5
	32	8	8	2	2	2/5	5
	33	8	12	2	2	2/5	5
	34	12	12	2	2	5	5
	35	12	12	3	4	5	5
September	36	12	12	3	4	6	5
	37	12	12	3	4	6	7
	38	12	12	12	12	6	7
	39	12	1	12	12	5	7
October	40	12	1/10	12	12	5	5
	41	12	1/10	12	12	5	5
	42	12	1/10	12	12	12	12
	43	12	12	12	12	12	12
	44	12	12	12	12	12	12
November	45	12	12	9	9	12	12
	46	12	12	9	9	12	12
	47	12	12	9	9	12	12
	48	12	12	9	9	9	9
December	49	9	1	9	9	9	9
	50	9	1	9	9	9	9
	51	9	1	9	9	9	9
	52	9	1	9	9	9	9

Appendix D

Spawning group abundance and relative size data. The following table provides the estimated range for total stock size and ranges for the relative proportions of each spawning subgroup.

Total Stock Size: N(300,100) thousand tonnes

Spawning	Spawning	Minimum	Maximum	Expected	Spawning	Spawning
Subgroup	Subgroup	Proportion	Proportion	Proportion	Zone	Period
Index	Name	(%)	(%)	(%)	(No.)	(Dates)
1	Scots Bay, Chedabucto	5.25	18.75	12	8	July 20 -Aug 15
2	Scots Bay, Grand Manan	1.75	6.25	3	8	July 20 - Aug 15
3	Trinity	10	30	20	3	Aug 15 -Sept 15
4	German Bank	20	60	40	7	Sept 1 -Oct 15
5	Seal Island	10	30	20	6	Sept 1 -Oct 15
6	Lurcher	2	10	5	4	Aug 15 - Sept 15

Appendix E

Pascal program to simulate herring migration and obtain probability transition matrices for each zone over each week.

program fish_model(input,output);

{This program is designed to simulate fish migration of herring in the 4WX region of the Bay of Fundy.}

type

wavearray = array[1..6,1..5] of real;

grouparray = array[1..6] of real;

incmatrix = array[1..2,1..6,0..52] of integer;

popmatrix = array[0..52,1..15] of real;

transprobmatrix = array[1..150,1..10] of integer;

var i,j,k,l,l1,y,y1,y2,z,o,trial,totaltrials,m,prog,runs,week,z1,z2,sum,dummy: integer;

skip,totalskip,o3,o4,o5,o6,o7,o8,o9,o0,lm,randseed: integer;

ST,u1,u2,x1,c,d,realtotaltrials,reali,realsum,mort: real;

w: wavearray; b,p,minp,maxp: grouparray;

T: incmatrix; S: popmatrix; Q: transprobmatrix;

R: array[0..52,1..15,1..10] of integer;

oj: array[1..4,1..10,1..53] of integer;

fishdata_results1,results3: text;

{Important Note re: Zone Relabelling:

In order to conserve space since some zones are never visited by sufficient numbers of fish for a group to be considered in that location, those zones have been disregarded and other zones relabelled as a consequence. When the fish are diffuse they are now labelled as being in zone 12 rather than 0 or 99. The area off Halifax which was previously labelled as zone 18 is now labelled zone 14 so that there are now just 15 zones.

Throughout the program, except where otherwise indicated,

i is the index of the spawning group,

j is the index of the wave of the spawning group,

l is the index of week,

y, y1, and y2 are combined indices of zone and population level, and z is the index of zone.

o is the index of the choice between 2 possible locations of a wave of a group during a week.

trial is the index of trials and totaltrials is the desired number of trials.

w and p contain the fractions per wave and spawning group respectively.

T is the matrix whose entries are the location of the main wave of the ith group during the lth week.

S is the matrix whose entries are the populations in the zth zone during the lth week.

R is the array of matrices whose entries are 1 if there was a y1th combination level at the beginning of a week and the y2th at the end, and 0 otherwise.

Q is the experimentally determined transition matrix which is the average of

many trials.

mort is the coefficient of natural mortality. }

```
begin
assign(results1,'results1.dat');
rewrite(results1);
assign(results3,'pd10.dat');
rewrite(results3);
assign(fshdta,'new2fsh2.dat');
reset(fshdta);
totaltrials:= 500;
realtotaltrials:= totaltrials;
mort:= 0.2/52.0;
runs:= totaltrials div 10;
randseed:= 1;
```

```
for i:= 1 to 6 do
begin
read(fshdta.minp[i]);
read(fshdta.maxp[i]);
end;
```

{This section produces 2 matrices whose dimensions are time and spawning group.
Their entries are the location of the main wave of each group during each week. }

```
for o:= 1 to 2 do
begin
for l:= 1 to 52 do
begin
for i:= 1 to 6 do read(fshdta.T[o,l,i]);
end;{Week}
end;{Choice of 2 locations. }
```

{The program "runs" begin with 10 trials in each run. After each "run" has finished, the cumulative sum of the probabilities is stored in results1 to be later used for the total cumulative sum. }

```
for prog:= 1 to runs do
begin
```

{The trials begin. }

```
for trial:= 1 to 10 do
begin
```

{This section will generate random proportions for the relative strengths of the different spawning groups. }

{The first loop calculates the scaling factors so that the sum of the group proportions is equal to 1. }

```

c:= 1.0;
d:= 0.0
for i:= 1 to 6 do
begin
b[i]:= random;
c:= c - minp[i];
d:= d + maxp[i] * b[i];
end;
{The second loop calculates the proportions of the different spawning groups
so that they fall between each group's minimum and maximum levels.}
for i:= 1 to 6 do p[i]:= minp[i] + (b[i] * maxp[i] * c/d);

{This section generates a value for the total fish population from a
N(300,100) distribution.}
u1:= random;
u2:= random;
x1:= sqrt((-2.0)*ln(u1))*cos(2.0*pi*u2);
ST:= 300.0 + (100.0 * x1);

{This sub-section generates relative wave strengths for 5 waves in each spawning
group depending on which distribution is picked randomly.}
for i:= 1 to 6 do
begin
m:= random(5) + 1;
case m of
1: begin
for j:= 1 to 5 do w[i,j]:= 0.2;
end;
2: begin
w[i,1]:= 0.15;
w[i,2]:= 0.2;
w[i,3]:= 0.3;
w[i,4]:= 0.2;
w[i,5]:= 0.15;
end;
3: begin
w[i,1]:= 0.0;
w[i,2]:= 0.333;
w[i,3]:= 0.334;
w[i,4]:= 0.333;
w[i,5]:= 0.0;
end;
4: begin
w[i,1]:= 0.15;
w[i,2]:= 0.50;
w[i,3]:= 0.20;
w[i,4]:= 0.10;

```

```

    w[i,5]:= 0.05;
end;
5: begin
    w[i,1]:= 0.05;
    w[i,2]:= 0.10;
    w[i,3]:= 0.20;
    w[i,4]:= 0.50;
    w[i,5]:= 0.15;
end;
end; {Case.}
end; {ith group's distribution of wave strengths.}

```

{The matrix whose indices are week and zone and whose entries are equal to the total population of the zone for that week is initialized to 0.}

```

for l:= 1 to 52 do
begin
    for z:= 1 to 15 do S[l,z]:= 0.0;
end;
end;

```

{This loop puts the population of each wave of each group into the correct zone.}

{j = 0 is the location of the main wave.}

```

for l:= 1 to 52 do
begin
    for i:= 1 to 6 do
begin
    if (i=1) or (i=2) then o:= 1
        else begin
            oj[i-2,trial,1]:= random(2) + 1;
            o:= oj[i-2,trial,1];
        end;

    for j:= -2 to 2 do
begin
        k:= 1 - j;
        {This corrects year-end turnaround.}
        if (k>52) then k:= k - 52
            else if (k<1) then k:= k + 52;
        z:= T[o,i,k];
        S[l,z]:= S[l,z]+(p[i]*w[i,j+3])*ST;
    end; {Wave.}
end; {Group.}
    ST:= ST*(1.0 - mort); {The total stock strength is reduced by the weekly natural mortality.}
end; {Week.}

```

```

for l:= 1 to 52 do
begin
    {if (l=1) or (l=2) then write(results3,'week is ',l);}
end;

```

```

for z:= 1 to 15 do
begin
{The array RI holds the population level of each zone at the end of each week.}
if (S[L,z] = 0.0000) then RI[l,z,trial]:= 1
else for i:= 1 to 4 do if (S[L,z] <= i*25) and (S[L,z] > (i-1)*25)
then RI[l,z,trial]:= i+1;
if (S[L,z] > 100) then for i:= 5 to 8
do if (S[L,z] > (i-3)*50) and (S[L,z] <= (i-2)*50)
then RI[l,z,trial]:= i+1;
if (S[L,z] > 300) then RI[l,z,trial]:= 10;

end;
end;
end;

```

```

for l:= 1 to 52 do
begin
{Initialize the trial probability transition matrix to 0.}
for y1:= 1 to 150 do
begin
for y2:= 1 to 5 do Q[y1,y2]:= 0;
end; {Initial state.}

for trial:= 1 to 10 do
begin
for z:= 1 to 15 do
begin
if (l=1) then lm:= 1
else lm:= l-1;
i:= RI[lm,z,trial]; {Initial zone population level at week's start.}
j:= RI[l,z,trial]; {Terminal zone population level at week's end.}
y1:= i+(z-1)*10;
y2:= j;
Q[y1,y2]:= Q[y1,y2] + 1;
end; { Zone.}
end; { Trial.}

```

```

for y1:= 1 to 15 do
begin
for i:= 1 to 10 do
begin
z1:= (y1-1)*10+i;
for j:= 1 to 9 do
begin
z2:= j;
write(results1,Q[z1,z2],');

```

```

    end;
    writeln(results1,Q[z1,z2+1]');
    end;{Line of probability transition matrix.}
    end;{Zone.}
    end;{Week.}
end;{Program "runs".}

{All cumulative sums are now added cumulatively again and printed.}
totalskip:= 51 * 150;{Number of lines between the matrix for a week from one
run to the next.}
for l:= 1 to 52 do
begin
    reset(results1);
    for y1:= 1 to 150 do
    begin
        for y2:= 1 to 5 do Q[y1,y2]:= 0;
    end;

    {Perform the cumulative sum.}
    for prog:= 1 to runs do
    begin
{On the first run of the sum go to the correct week's results.}
        if (prog = 1) then if (l>1)
            then for skip:= 1 to (l-1)*150 do readln(results1,dummy);
        for y1:= 1 to 150 do
        begin
            for y2:= 1 to 10 do
            begin
                if (y2<10) then read(results1,dummy)
                    else readln(results1,dummy);
                Q[y1,y2]:= Q[y1,y2]+dummy;
            end;{y2}
        end;{y1}
        {Skip the matrices for the intervening weeks and go to that for the next run.}
        if (prog<runs) then for skip:= 1 to totalskip do readln(results1,dummy);
    end;{Program "run".}

{Print the titles for the matrices.}
    {writeln(results3,'The probability transition matrix for week 'l' is:');
    writeln(results3,y1 1 2 3 4 5 6 7 8 9 10);}
    for y1:= 1 to 150 do {Change to produce probability transition matrix for zone y1.}
    begin
        sum:= 0;
        for y2:= 1 to 10 do sum:= sum + Q[y1,y2];
        {if (y1<10) then write(results3,dummy,' ');
        else write(results3,dummy,' ');}
        dummy:= y1 mod 10;
    end;

```

```

if (dummy=0) then dummy:= 10;
for y2:= 1 to 10 do
begin
  if (sum>0) then begin
    {if (Q[y1,y2] < 300)
    then i:= ((Q[y1,y2]*100) div sum)
    else i:= ((Q[y1,y2]*50) div (sum div 2));}
    reali:= Q[y1,y2];
    realsum:= sum;
    reali:= reali/realsum;
  end
  else if ((y1 mod 10)=y2) then reali:=1.00
    else reali:= 0.0;
  if (sum=0) and (((y1 mod 10)=0) and (y2=10)) then reali:= 1.00;
  write(results3,reali,',');
end; {y2}
writeln(results3,',');
end; {y1}
end; {week}
close(results1);
close(results3);
reset(results3);
end.

```

Appendix F

Discretized catch data for years 1991-1995.

The zones are grouped into 6 classes with respect to the signal matrix and catch data. For all zones, a catch signal of 1 indicates that no fish were caught. Weeks 51-52 are not included as there are no catches during these weeks.

Class 1 contains Zones 6, 7, and 8 except for the spawning periods in areas 6 and 7 when they are classified as class 5 instead. Catch levels for class 1 are as follows:

Catch Level	Catch Values
2	0 < catch < 500 tonnes
3	500 < catch < 1000 tonnes
4	1000 < catch < 1500 tonnes
5	1500 < catch < 2000 tonnes
6	2000 < catch < 2500 tonnes
7	2500 < catch < 3000 tonnes
8	3000 < catch < 3500 tonnes
9	3500 < catch < 4000 tonnes
10	4000 < catch < 4500 tonnes
11	4500 < catch < 5000 tonnes
12	5500 < catch < 5500 tonnes
13	catch > 5500 tonnes

Class 2 includes Zones 1, 2, 3, and 5. Catch levels for class 2 are as follows:

Catch Level	Catch Values
2	0 < catch < 250 tonnes
3	250 < catch < 500 tonnes
4	500 < catch < 750 tonnes
5	750 < catch < 1000 tonnes
6	1000 < catch < 1250 tonnes
7	1250 < catch < 1500 tonnes
8	1500 < catch < 1750 tonnes
9	catch > 1750 tonnes

Zones 4, 10, 11, 13, 14, and 15 are contained in class 3. Catch levels for class 3 are as follows:

Catch Level	Catch Values
2	0 < catch < 50 tonnes
3	50 < catch < 100 tonnes
4	100 < catch < 150 tonnes
5	150 < catch < 200 tonnes
6	200 < catch < 250 tonnes
7	catch > 250 tonnes

Class 4 consists of Zone 9 only. Catch levels for class 4 are as follows:

Catch Level	Catch Values
2	500 ≥ catch > 0 tonnes
3	1000 ≥ catch > 500 tonnes
4	1500 ≥ catch > 1000 tonnes
5	2000 ≥ catch > 1500 tonnes
6	2500 ≥ catch > 2000 tonnes
7	3000 ≥ catch > 2500 tonnes
8	3500 ≥ catch > 3000 tonnes
9	4000 ≥ catch > 3500 tonnes
10	4500 ≥ catch > 4000 tonnes
11	5000 ≥ catch > 5500 tonnes
12	catch > 5000 tonnes

Catch levels for class 5 are the same as the class levels for class 1 as the zones in class 5 are also contained in class 1. Since class 6 exists only to classify Zone 12 and no signal from this zone is ever used, class 6 only has 1 catch level (0).

For purposes of checking that total catch of the discretized levels approximates total actual catch, the expected catch of each level was set to the midpoint of the catch level. For each year, total discretized catch fell within 10% of the actual purse seine catch for the year.

Year	1991	1992	1993	1994	1995
Actual Catch (tonnes)	88,838	96,415	92,223	75,593	56,416
Discretized Catch (tonnes)	94,550	100,900	95,700	73,025	55,850

The following tables each contain the discretized catch data, for a single year.

1991

Week \ Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1
2	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1
3	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	1	2	2	1	1	1	2	1	1	1	2	1	1	1	1
23	1	3	2	2	2	1	2	1	1	1	2	1	1	1	1
24	1	4	1	2	4	2	2	1	1	1	1	1	1	1	1
25	3	4	2	2	3	1	7	1	1	1	3	1	1	1	1
26	4	9	1	1	2	1	2	1	1	1	1	1	1	1	1
27	5	8	1	2	3	1	5	1	1	1	5	1	1	1	1
28	3	5	1	1	2	1	6	1	1	3	1	1	7	1	1
29	2	6	1	1	2	1	5	7	1	1	1	1	7	1	1
30	1	5	2	1	2	3	2	2	1	1	1	1	2	1	2
31	1	2	1	2	5	2	2	5	1	3	1	1	1	1	2
32	1	2	2	1	4	2	2	11	1	3	3	1	1	1	1
33	1	2	5	1	3	1	2	2	1	1	1	1	1	1	1
34	1	2	2	1	1	7	2	1	1	1	1	1	1	1	1
35	1	2	2	1	1	12	2	1	1	1	3	1	1	1	1
36	1	1	2	1	3	6	5	1	1	1	1	1	1	1	1
37	1	1	9	1	5	2	11	1	1	1	1	1	1	1	1
38	2	3	3	1	4	2	13	1	1	1	1	1	1	1	1
39	2	3	1	1	2	6	8	1	1	1	1	1	1	1	1
40	5	3	1	1	1	3	1	1	1	3	1	1	1	1	1
41	3	3	1	1	6	2	1	1	1	7	1	1	1	1	1
42	2	2	1	1	1	1	2	1	1	2	1	1	1	1	1
43	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
44	2	2	1	1	1	1	1	1	2	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	6	1	1	1	1	1	1
46	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
47	1	1	1	1	1	1	1	1	4	1	1	1	1	1	1
48	1	1	1	1	1	1	1	1	4	1	1	1	1	1	1
49	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

1992

Week \ Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	2	1	1	1	1	1	1	1	5	1	1	1	1	1	1
3	2	1	1	1	1	1	1	1	4	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	7	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	2	1	1	2	1	1	1	7	1	1	1	1
23	2	3	1	1	3	1	1	1	1	7	1	1	1	1	1
24	4	3	1	1	6	2	1	1	1	7	1	1	1	1	1
25	2	2	3	2	8	1	2	1	1	7	1	1	1	1	1
26	2	6	9	4	2	1	1	1	1	7	1	1	1	1	1
27	2	5	5	7	9	1	3	1	1	1	1	1	1	1	1
28	1	4	4	7	6	1	3	3	1	1	1	1	1	1	1
29	1	3	4	7	5	1	4	4	1	7	1	1	1	1	1
30	1	3	2	7	9	2	2	5	1	1	1	1	4	1	1
31	1	3	1	1	4	2	1	6	1	2	1	1	1	1	1
32	1	1	2	1	2	3	1	8	1	1	2	1	1	1	1
33	1	2	2	1	1	3	1	4	1	1	1	1	1	1	1
34	1	1	2	1	1	3	1	1	1	1	1	1	1	1	1
35	1	1	1	1	3	3	2	1	1	1	1	1	1	1	1
36	1	1	1	1	2	8	3	1	1	1	1	1	1	1	1
37	1	1	2	1	1	13	8	1	1	1	1	1	1	1	1
38	1	1	1	1	9	6	13	1	1	1	1	1	1	1	1
39	1	2	1	1	2	1	13	1	1	1	1	1	1	1	1
40	3	6	2	1	4	1	2	1	1	5	1	1	1	1	1
41	2	3	1	1	3	1	1	1	1	7	1	1	1	1	1
42	3	3	1	1	3	1	1	1	1	1	1	1	1	1	1
43	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
44	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
45	4	1	1	1	1	1	1	1	6	1	1	1	1	1	1
46	1	1	1	1	1	1	1	1	6	1	1	1	1	1	1
47	1	1	1	1	1	1	1	1	6	1	1	1	1	1	1
48	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
49	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

1993

Week \ Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2	1	1	1	1	1	1	1	3	1	1	1	1	1	1
2	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1
3	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	1	2	1	1	1	1	1	1	1	1	6	1	1	1	1
19	1	2	1	1	1	1	1	1	1	1	6	1	1	1	1
20	1	2	1	1	1	1	1	1	1	1	5	1	1	1	1
21	1	2	1	1	1	2	1	1	1	1	5	1	1	1	1
22	1	1	1	1	1	2	2	1	1	1	6	1	1	1	1
23	2	3	1	1	1	5	6	1	1	1	6	1	1	1	1
24	2	3	1	7	7	2	4	1	1	1	7	1	1	1	1
25	2	4	2	5	6	1	4	1	1	3	7	1	1	1	1
26	2	3	1	5	6	1	5	1	1	1	1	1	1	1	1
27	1	1	1	7	9	3	7	1	1	1	7	1	1	1	1
28	1	2	1	7	2	5	5	1	1	1	6	1	7	1	1
29	1	4	3	7	3	4	7	1	1	6	3	1	7	1	1
30	1	2	4	7	5	5	1	3	1	6	1	1	7	1	1
31	1	1	1	1	1	1	1	6	1	1	1	1	1	1	1
32	1	6	1	1	2	1	1	4	1	1	1	1	1	1	1
33	1	5	1	1	3	1	1	4	1	1	1	1	1	1	1
34	1	5	3	5	7	1	1	2	1	1	1	1	1	1	1
35	1	6	2	6	2	1	1	4	1	1	1	1	1	1	1
36	1	1	6	7	6	6	1	1	1	1	1	1	1	1	1
37	1	1	6	7	6	6	1	1	1	1	1	1	1	1	1
38	4	1	1	1	1	3	1	1	1	1	1	1	1	1	1
39	1	1	1	1	4	3	3	1	1	1	1	1	1	1	1
40	1	1	1	1	1	4	4	1	1	4	1	1	1	1	1
41	7	1	1	1	1	5	5	1	1	6	1	1	1	1	7
42	3	5	1	1	1	3	3	1	1	7	1	1	1	1	7
43	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1
44	3	1	1	1	1	1	1	1	3	1	1	1	1	1	1
45	3	1	1	1	1	1	1	1	6	1	1	1	1	1	1
46	3	1	1	1	1	1	1	1	3	1	1	1	1	1	1
47	3	1	1	1	1	1	1	1	5	1	1	1	1	1	1
48	3	1	1	1	1	1	1	1	3	1	1	1	1	1	1
49	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
50	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1

1994

Week \ Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1
18	1	2	1	1	1	1	1	1	1	1	7	1	1	1	1
19	1	2	1	1	1	1	1	1	1	1	7	1	1	1	1
20	1	2	1	1	1	1	1	1	1	1	5	1	1	1	1
21	1	2	1	1	1	2	2	1	1	1	7	1	1	1	1
22	1	1	1	1	1	2	2	1	1	1	3	1	1	1	1
23	1	2	1	1	1	2	2	1	1	1	7	1	7	1	1
24	1	3	1	5	4	2	2	1	1	1	7	1	1	1	1
25	1	2	1	3	4	1	1	1	1	3	7	1	1	1	1
26	1	4	2	1	1	2	2	1	1	1	1	1	1	1	1
27	1	4	1	7	1	1	6	3	1	1	1	1	1	1	1
28	1	6	1	7	2	1	5	2	1	4	7	1	1	1	1
29	6	2	1	1	1	1	4	3	1	2	1	1	3	1	1
30	1	8	1	1	1	1	4	3	1	2	1	1	1	1	1
31	1	4	1	1	4	1	1	8	1	1	1	1	1	1	1
32	1	5	2	1	2	1	1	6	1	1	1	1	1	1	1
33	1	2	1	1	4	1	1	4	1	1	1	1	1	1	1
34	1	4	3	1	2	1	1	4	1	1	1	1	1	1	1
35	1	3	1	1	2	1	1	3	1	2	1	1	1	1	1
36	1	1	1	1	1	3	6	1	1	1	1	1	1	1	1
37	1	1	5	1	1	2	8	1	1	1	1	1	1	1	1
38	4	1	3	1	1	3	7	1	1	1	1	1	1	1	1
39	1	1	1	1	6	4	9	1	1	1	1	1	1	1	4
40	6	3	1	1	1	4	5	1	1	5	1	1	1	1	1
41	6	1	1	1	1	5	3	1	1	1	1	1	1	1	5
42	6	1	1	1	1	1	2	1	1	1	1	1	1	1	5
43	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1
44	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
45	3	1	1	1	1	1	1	1	2	1	1	1	1	1	1
46	3	1	1	1	1	1	1	1	2	1	1	1	1	1	1
47	3	1	1	1	1	1	1	1	2	1	1	1	1	1	1
48	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
49	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

1995

Week \ Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1
2	4	1	1	1	1	1	1	1	3	1	1	1	1	1	1
3	3	1	1	1	1	1	1	1	2	1	1	1	1	1	1
4	5	1	1	1	1	1	1	1	2	1	1	1	1	1	1
5	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	2	2	1	1	1	1	5	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1	7	1	3	1	1
25	1	1	1	1	1	1	3	1	1	1	1	1	1	1	1
26	1	2	2	1	1	1	6	1	1	1	1	1	1	1	1
27	2	4	2	3	2	1	6	1	1	1	3	1	1	1	1
28	3	6	1	1	1	2	1	1	1	1	5	1	1	1	1
29	5	6	1	1	1	1	2	1	1	1	1	1	1	1	1
30	1	3	1	1	1	1	1	5	1	1	1	1	2	1	1
31	2	5	2	4	2	1	1	1	1	1	1	1	1	1	1
32	1	4	2	3	2	2	2	1	1	1	1	1	1	1	1
33	1	8	1	1	2	1	1	1	1	1	1	1	2	1	1
34	1	8	1	1	5	1	1	1	1	1	1	1	1	1	1
35	2	1	1	2	5	2	1	1	1	1	1	1	1	1	1
36	1	2	1	1	1	8	2	1	1	1	1	1	1	1	1
37	3	1	2	1	1	3	3	6	1	1	1	1	1	1	1
38	2	3	1	1	1	3	7	1	1	1	1	1	1	1	1
39	2	4	1	5	8	3	8	1	1	3	1	1	4	1	1
40	6	3	2	1	3	2	2	1	1	1	7	1	7	1	1
41	3	2	1	1	2	1	2	1	1	7	7	1	1	1	1
42	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
43	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
44	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
45	3	1	1	1	1	1	1	1	3	1	1	1	1	1	1
46	3	1	1	1	1	1	1	1	2	1	1	1	1	1	1
47	2	1	1	1	1	1	1	1	3	1	1	1	1	1	1
48	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
49	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Appendix G

The signal matrix Q .

The signal matrix Q relates catch data to population level. Each block of 10 rows is the signal matrix for a class of zones. The row represents a given population level in a zone, the column denotes a catch level, and the entry is the conditional probability that, given that population level, a catch of that level is made.

Zones	Catch / State	1	2	3	4	5	6	7	8	9	10	11	12	13
6,7,8	1	02.81	0.08	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	2	0.56	0.16	0.08	0.06	0.06	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	3	0.31	0.24	0.15	0.11	0.11	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	4	0.23	0.12	0.08	0.06	0.11	0.08	0.1	0.11	0.05	0.03	0.01	0.01	0.01
	5	0.14	0.01	0.01	0.01	0.1	0.16	0.2	0.2	0.09	0.05	0.01	0.01	0.01
	6	0.12	0.01	0.01	0.01	0.06	0.1	0.15	0.18	0.13	0.09	0.06	0.05	0.03
	7	0.1	0.01	0.01	0.01	0.01	0.05	0.1	0.15	0.17	0.14	0.1	0.1	0.05
	8	0.06	0.01	0.01	0.01	0.01	0.03	0.05	0.13	0.16	0.15	0.12	0.14	0.12
	9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.11	0.14	0.16	0.14	0.19	0.19
	10	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.14	0.16	0.15	0.25
1,2,3,5	1	0.92	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01				
	2	0.71	0.15	0.06	0.02	0.02	0.01	0.01	0.01	0.01				
	3	0.49	0.3	0.1	0.03	0.03	0.02	0.01	0.01	0.01				
	4	0.36	0.25	0.1	0.07	0.07	0.06	0.05	0.03	0.01				
	5	0.24	0.2	0.1	0.1	0.1	0.1	0.1	0.05	0.01				
	6	0.17	0.2	0.12	0.13	0.12	0.1	0.1	0.05	0.01				
	7	0.1	0.2	0.14	0.15	0.15	0.1	0.1	0.05	0.01				
	8	0.1	0.15	0.12	0.13	0.15	0.12	0.13	0.07	0.03				
	9	0.1	0.1	0.1	0.1	0.15	0.15	0.15	0.1	0.05				
	10	0.1	0.07	0.08	0.1	0.15	0.15	0.2	0.1	0.05				
4,10,11, 13,14,15	1	0.94	0.01	0.01	0.01	0.01	0.01	0.01						
	2	0.82	0.13	0.01	0.01	0.01	0.01	0.01						
	3	0.7	0.25	0.01	0.01	0.01	0.01	0.01						
	4	0.6	0.3	0.06	0.01	0.01	0.01	0.01						
	5	0.5	0.35	0.11	0.01	0.01	0.01	0.01						
	6	0.43	0.3	0.13	0.06	0.06	0.01	0.01						
	7	0.35	0.26	0.15	0.1	0.12	0.01	0.01						
	8	0.28	0.18	0.17	0.15	0.13	0.04	0.05						
	9	0.2	0.1	0.2	0.2	0.12	0.07	0.11						
	10	0.15	0.1	0.2	0.2	0.17	0.07	0.11						
9	1	0.9	0.01	0.01	0.1	0.06	0.03	0.01	0.01	0.01	0.01	0.01	0.0	
	2	0.53	0.1	0.13	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.0
	3	0.2	0.1	0.24	0.2	0.1	0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	4	0.15	0.1	0.2	0.22	0.15	0.11	0.02	0.01	0.01	0.01	0.01	0.01	0.01
	5	0.1	0.1	0.18	0.2	0.15	.15	0.07	0.01	0.01	0.01	0.01	0.01	0.01
	6	0.1	0.1	0.1	0.2	0.2	0.14	0.05	0.04	0.04	0.04	0.01	0.01	0.01
	7	0.1	0.1	0.1	0.12	0.18	0.2	0.07	0.05	0.04	0.02	0.01	0.01	0.01
	8	0.05	0.05	0.06	0.1	0.12	0.15	0.1	0.11	0.1	0.07	0.06	0.03	
	9	0.05	0.05	0.05	0.05	0.1	0.1	0.15	0.1	0.1	0.1	0.1	0.05	
	10	0.05	0.03	0.03	0.05	0.1	0.1	0.1	0.12	0.12	0.1	0.1	0.1	
6,7	1	0.84	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	2	0.57	0.14	0.08	0.06	0.06	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	3	0.3	0.23	0.14	0.11	0.11	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	4	0.22	0.12	0.08	0.06	0.1	0.1	0.11	0.1	0.05	0.03	0.01	0.01	0.01
	5	0.14	0.01	0.01	0.01	0.1	0.16	0.2	0.2	0.09	0.05	0.01	0.01	0.01
	6	0.1	0.01	0.01	0.01	0.07	0.11	0.12	0.15	0.1	0.1	0.07	0.08	0.07
	7	0.1	0.01	0.01	0.01	0.05	0.05	0.05	0.1	0.1	0.15	0.13	0.12	0.12
	8	0.1	0.01	0.01	0.01	0.03	0.05	0.05	0.1	0.1	0.12	0.15	0.14	0.13

	9	0.1	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.1	0.1	0.1	0.15	0.15	0.16
	10	0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.1	0.1	0.1	0.15	0.15	0.2
12	1	1.0													
	2	1.0													
	3	1.0													
	4	1.0													
	5	1.0													
	6	1.0													
	7	1.0													
	8	1.0													
	9	1.0													
	10	1.0													

Appendix H

Sensitivity analysis.

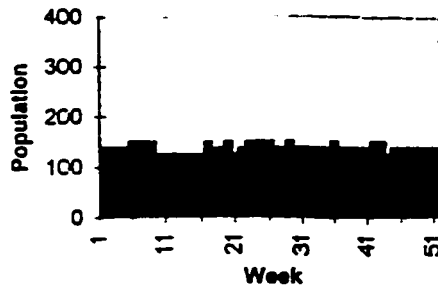
The sensitivity analysis was carried out as described in Section 5.1 to determine how closely the model estimated true abundance. Results for all trials are summarized in 4 of Section 6.1. A sample run for each population level is provided in the tables of this Appendix.

The sensitivity analysis was run 10 times for each fixed stock population level: “low”= 138 thousand tonnes, “medium” = 238 thousand tonnes, and “high” =338 thousand tonnes. These tables present columns for each week of actual population level, generated catch observation, updated total population estimate, and difference between actual and estimated population size. Graphical weekly spreadsheet output for these results are also provided.

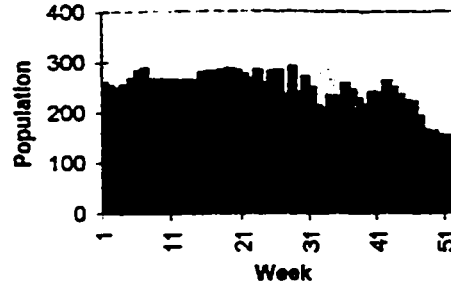
Trial No.	Random Number Seed
1	741598362
2	489326571
3	123456789
4	521734698
5	987654321
6	243165978
7	829613547
8	738941256
9	526843719
10	369842157

Week	Actual Pop (thousand T)	Actual Catch (Tons)	Exp Pop (thousand T)	Difference: Exp-Actual
1	138	3250	279	141
2	138	0	280	122
3	138	1750	254	116
4	138	1250	248	110
5	138	750	254	116
6	150	125	267	117
7	150	0	282	132
8	150	2375	287	137
9	150	0	266	116
10	125	0	265	140
11	125	0	265	140
12	125	0	264	139
13	125	0	263	138
14	125	0	263	138
15	125	0	262	137
16	125	0	279	154
17	150	0	281	131
18	138	0	279	142
19	138	0	284	146
20	150	0	286	136
21	125	0	282	157
22	138	0	274	137
23	150	125	266	116
24	150	3500	284	134
25	150	625	258	108
26	150	1150	281	131
27	138	1875	283	145
28	138	550	234	97
29	150	3025	290	140
30	138	1925	239	101
31	138	3125	269	132
32	138	1625	250	112
33	138	2125	213	75
34	138	125	208	70
35	138	875	232	94
36	150	2375	230	80
37	138	5500	257	120
38	138	750	244	107
39	138	0	227	90
40	138	0	213	76
41	138	4625	240	102
42	150	1375	238	88
43	150	0	262	112
44	125	0	250	125
45	138	0	234	96
46	138	125	223	85
47	138	1250	220	83
48	138	750	191	53
49	138	375	163	25
50	138	0	161	23
51	138	0	153	15
52	125	0	152	27
min	125	0	152	15
max	150	5500	290	157
ave	138	863	248	109
stdev	9	1290	35	35
total	7063	47275	12907	5568

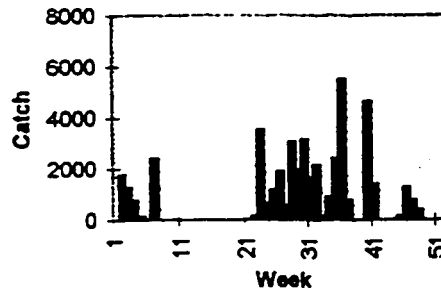
Actual Population
(thousand tonnes)



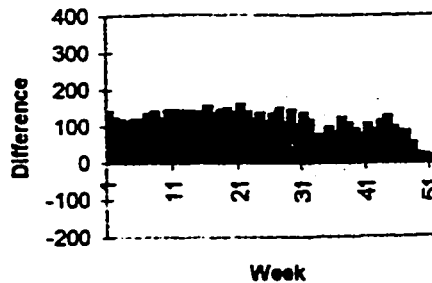
Expected Population
(thousand tonnes)



Simulated Catch
(tonnes)

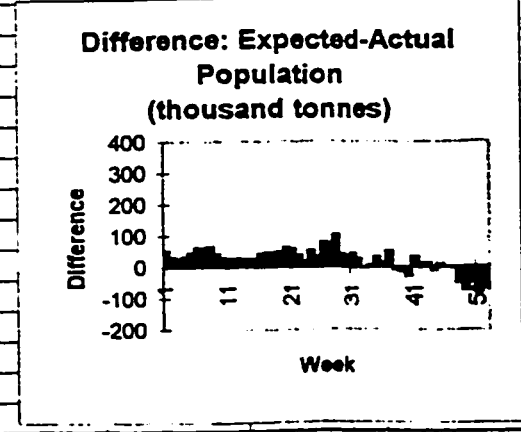
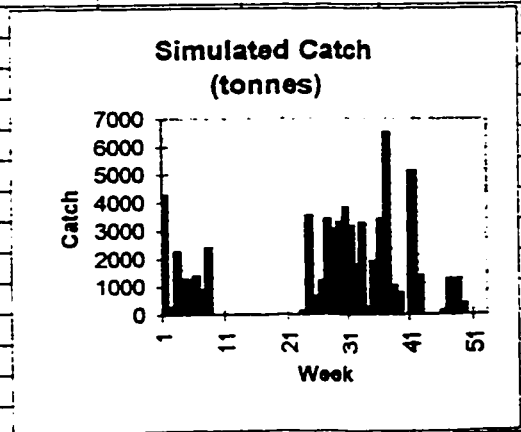
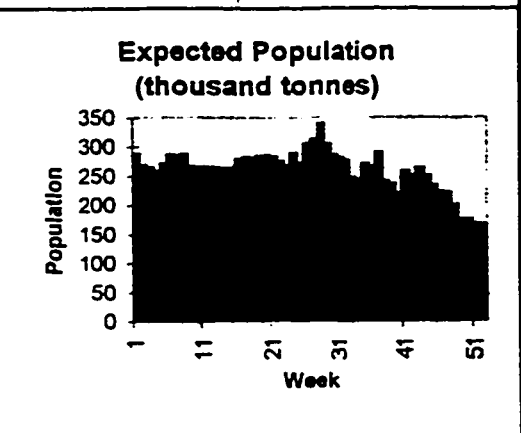
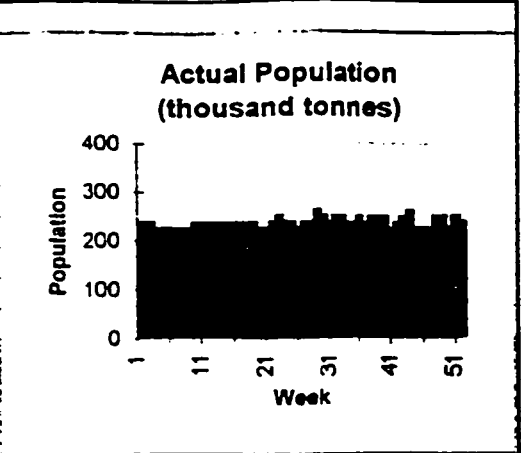


Difference: Expected-Actual
Population
(thousand tonnes)



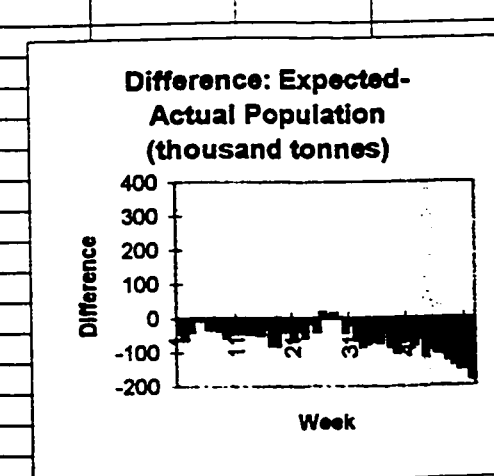
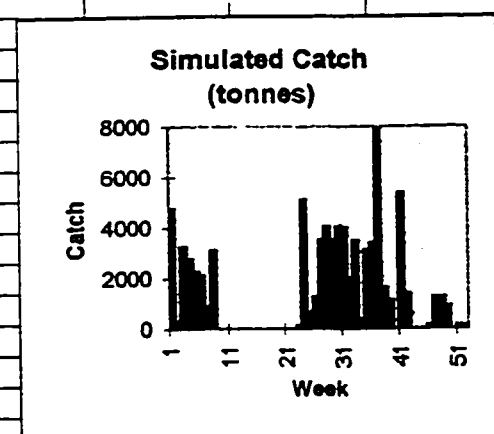
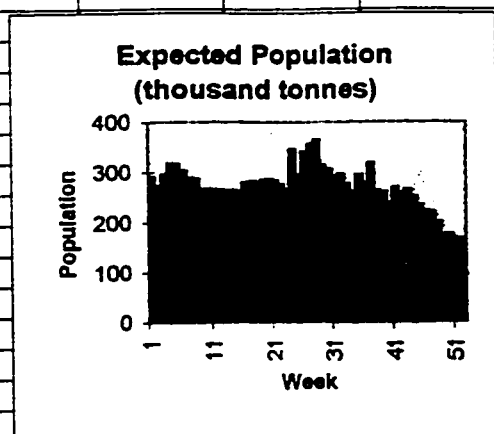
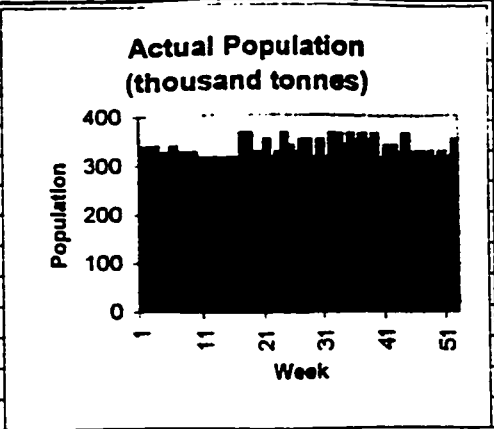
Define trial Actual Population "medium" = 233 kt, Random seed = 741573362

Week	Actual Pop (thousand T)	Sim Catch (Tons)	Exp Pop (thousand T)	Difference: Exp-Actual
1	238	4250	288	51
2	238	250	268	31
3	238	2250	264	27
4	225	1250	258	33
5	225	1250	270	45
6	225	1375	287	62
7	225	875	285	60
8	225	2375	287	62
9	225	0	266	41
10	238	0	265	28
11	238	0	265	27
12	238	0	264	27
13	238	0	263	26
14	238	0	263	25
15	238	0	262	24
16	238	0	279	41
17	238	0	281	44
18	238	0	279	42
19	238	0	284	46
20	225	0	286	61
21	225	0	282	57
22	238	0	274	37
23	250	125	266	16
24	238	3525	289	51
25	238	650	271	33
26	225	1200	304	79
27	238	3375	313	76
28	238	3050	339	101
29	263	3275	304	42
30	250	3800	285	35
31	238	3125	281	44
32	250	1750	276	26
33	250	3250	247	-3
34	238	250	243	5
35	238	1875	270	32
36	250	3375	265	15
37	238	6500	289	52
38	250	1000	240	-10
39	250	750	235	-15
40	250	0	219	-31
41	225	5125	257	32
42	238	1375	250	12
43	250	0	263	13
44	263	0	250	-13
45	225	0	234	9
46	225	125	223	-2
47	225	1250	220	-5
48	250	1250	200	-50
49	250	375	174	-76
50	225	0	174	-51
51	250	0	166	-84
52	238	0	165	-72
min	225	0	165	-84
max	263	6500	339	101
ave	238	1236	260	22
stdev	10	1590	36	39
total	12375	64250	13368	1158



Define trial Actual Population. "high" = 338 kg, Random No Seed = 741598362

Week	Actual Pop (thousand T)	Sim Catch (Tons)	Exp Pop (thousand T)	Difference: Exp-Actual
1	338	4750	291	-46
2	338	250	272	-66
3	338	3250	296	-42
4	325	2750	317	-8
5	325	2250	315	-10
6	338	2125	303	-34
7	325	875	288	-37
8	325	3125	286	-39
9	325	0	266	-59
10	313	0	265	-47
11	313	0	265	-48
12	313	0	264	-48
13	313	0	263	-49
14	313	0	263	-50
15	313	0	262	-51
16	313	0	279	-34
17	363	0	281	-81
18	363	0	279	-83
19	325	0	284	-41
20	325	0	286	-39
21	350	0	282	-68
22	313	0	274	-38
23	325	125	266	-59
24	363	5125	345	-18
25	338	650	295	-42
26	325	1275	341	16
27	350	3525	357	7
28	350	4050	365	15
29	313	3525	313	1
30	350	4050	305	-45
31	313	4000	292	-21
32	363	2000	295	-67
33	363	3500	276	-86
34	338	375	260	-77
35	363	3125	294	-69
36	350	3375	273	-77
37	363	7875	317	-45
38	350	1625	262	-88
39	363	1125	259	-103
40	313	0	238	-74
41	338	5375	269	-69
42	338	1375	258	-80
43	325	0	264	-81
44	363	0	250	-113
45	325	0	234	-91
46	325	125	223	-102
47	325	1250	220	-105
48	325	1250	200	-125
49	313	875	174	-138
50	325	0	174	-151
51	313	125	167	-146
52	350	125	167	-183
min	313	0	167	-183
max	363	7875	365	16
ave	334	1523	272	-62
stdev	18	1881	43	42
total	17350	79075	13968	-3215



Appendix I

Perturbation Analysis: initial estimates on total population size for 1991 were set at various levels from 1 to 10, representing low to high population levels in Zone 9 at the beginning of the year, and then updated using equation (3.3). Weekly estimates of total stock size then converged within 8 weeks.

Initial Level / Week	1	2	3	4	5	6	7	8	9	10
1	113	132	147	166	191	206	224	240	260	306
2	109	120	131	148	177	201	210	220	237	299
3	122	128	136	149	179	215	219	224	233	291
4	169	174	179	189	211	238	240	243	248	285
5	212	216	219	226	242	260	262	264	267	291
6	257	258	258	260	264	271	272	272	273	284
7	282	282	282	282	282	282	282	282	282	283
8	281	281	281	281	281	281	281	281	281	281

Appendix J

Tables of weekly estimates of spawning area populations and total population across all zones (thousand tonnes).

Year	1991					
Week	Scots Bay(Z8)	Trinity(Z3)	Lurcher(Z4)	Seal Island(Z6)	German Bank(Z7)	Total
1	0	0	0	0	0	252
2	0	0	0	0	0	214
3	0	0	0	0	0	196
4	0	0	0	0	0	218
5	0	0	0	0	0	247
6	0	0	0	0	0	266
7	0	0	0	0	0	282
8	0	0	0	0	0	281
9	0	0	0	0	0	266
10	0	0	0	0	0	265
11	0	0	0	0	0	265
12	0	0	0	0	0	264
13	0	0	0	0	0	263
14	0	0	0	0	0	263
15	0	0	0	0	0	262
16	0	0	0	0	0	279
17	0	0	0	0	0	281
18	0	0	0	0	0	279
19	0	0	0	0	7	284
20	0	0	0	0	14	286
21	0	0	0	0	22	282
22	0	0	8	0	27	264
23	0	0	23	0	24	276
24	0	0	40	0	22	298
25	0	0	51	0	61	372
26	0	0	46	5	19	290
27	0	0	60	13	72	353
28	9	0	56	15	83	347
29	13	0	39	14	54	338
30	20	0	23	15	22	310
31	33	0	13	7	8	348
32	36	0	0	0	0	316
33	27	11	10	0	0	300
34	14	24	13	10	0	266
35	10	39	13	20	14	258
36	0	46	13	53	42	286
37	0	36	13	45	93	319
38	0	25	13	34	130	352
39	0	10	10	24	110	341
40	0	0	0	12	61	286
41	0	0	0	0	13	272
42	0	0	0	0	0	258
43	0	0	0	0	0	264
44	0	0	0	0	0	262
45	0	0	0	0	0	252
46	0	0	0	0	0	248
47	0	0	0	0	0	264
48	0	0	0	0	0	255

49	0	0	0	0	0	226
50	0	0	0	0	0	230
51	0	0	0	0	0	221
52	0	0	0	0	0	220

Year	1992					
Week	Scots Bay(Z8)	Trinity(Z3)	Lurcher(Z4)	Seal Island(Z6)	German Bank(Z7)	Total
1	0	0	0	0	0	201
2	0	0	0	0	0	190
3	0	0	0	0	0	191
4	0	0	0	0	0	207
5	0	0	0	0	0	229
6	0	0	0	0	0	261
7	0	0	0	0	0	282
8	0	0	0	0	0	281
9	0	0	0	0	0	266
10	0	0	0	0	0	265
11	0	0	0	0	0	265
12	0	0	0	0	0	264
13	0	0	0	0	0	263
14	0	0	0	0	0	263
15	0	0	0	0	0	262
16	0	0	0	0	0	279
17	0	0	0	0	0	281
18	0	0	0	0	0	279
19	0	0	0	0	7	284
20	0	0	0	0	14	286
21	0	0	0	0	22	282
22	0	0	12	0	27	334
23	0	0	13	0	13	370
24	0	0	19	0	14	403
25	0	0	45	0	24	453
26	0	0	70	5	10	402
27	0	0	71	13	47	371
28	12	0	68	15	43	354
29	13	0	48	14	32	343
30	21	0	29	14	14	344
31	45	0	12	7	4	369
32	68	0	0	0	0	317
33	44	12	10	0	0	271
34	19	25	13	12	0	236
35	10	31	13	23	14	252
36	0	34	13	58	35	270
37	0	32	13	72	78	301
38	0	17	13	70	112	338
39	0	10	10	40	108	333
40	0	0	0	10	44	278
41	0	0	0	0	10	268
42	0	0	0	0	0	269
43	0	0	0	0	0	266
44	0	0	0	0	0	253
45	0	0	0	0	0	249
46	0	0	0	0	0	257
47	0	0	0	0	0	280
48	0	0	0	0	0	265

49	0	0	0	0	0	238
50	0	0	0	0	0	242
51	0	0	0	0	0	233
52	0	0	0	0	0	232

Year	1993					
Week	Scots Bay(Z8)	Trinity(Z3)	Lurcher(Z4)	Seal Island(Z6)	German Bank(Z7)	Total
1	0	0	0	0	0	209
2	0	0	0	0	0	193
3	0	0	0	0	0	201
4	0	0	0	0	0	226
5	0	0	0	0	0	252
6	0	0	0	0	0	275
7	0	0	0	0	0	283
8	0	0	0	0	0	281
9	0	0	0	0	0	266
10	0	0	0	0	0	265
11	0	0	0	0	0	265
12	0	0	0	0	0	264
13	0	0	0	0	0	263
14	0	0	0	0	0	263
15	0	0	0	0	0	262
16	0	0	0	0	0	279
17	0	0	0	0	0	281
18	0	0	0	0	0	317
19	0	0	0	0	7	364
20	0	0	0	0	14	371
21	0	0	0	0	22	364
22	0	0	8	0	27	376
23	0	0	13	0	39	403
24	0	0	22	0	28	428
25	0	0	46	0	28	471
26	0	0	82	5	53	485
27	0	0	78	16	92	434
28	9	0	72	18	80	348
29	13	0	52	18	69	363
30	21	0	31	18	9	311
31	43	0	12	4	4	284
32	41	0	0	0	0	282
33	32	9	10	0	0	304
34	18	22	13	9	0	320
35	12	37	13	17	10	302
36	0	60	13	45	27	307
37	0	60	13	73	41	336
38	0	33	13	45	48	274
39	0	11	10	29	35	278
40	0	0	0	12	23	255
41	0	0	0	0	12	248
42	0	0	0	0	0	242
43	0	0	0	0	0	262
44	0	0	0	0	0	262
45	0	0	0	0	0	258
46	0	0	0	0	0	261
47	0	0	0	0	0	276
48	0	0	0	0	0	260
49	0	0	0	0	0	256

50	0	0	0	0	0	260
51	0	0	0	0	0	250
52	0	0	0	0	0	249

Year	1994					
Week	Scots Bay(Z8)	Trinity(Z3)	Lurcher(Z4)	Seal Island(Z6)	German Bank(Z7)	Total
1	0	0	0	0	0	231
2	0	0	0	0	0	207
3	0	0	0	0	0	194
4	0	0	0	0	0	187
5	0	0	0	0	0	201
6	0	0	0	0	0	258
7	0	0	0	0	0	282
8	0	0	0	0	0	281
9	0	0	0	0	0	266
10	0	0	0	0	0	265
11	0	0	0	0	0	265
12	0	0	0	0	0	264
13	0	0	0	0	0	263
14	0	0	0	0	0	263
15	0	0	0	0	0	262
16	0	0	0	0	0	279
17	0	0	0	0	0	283
18	0	0	0	0	0	325
19	0	0	0	0	7	373
20	0	0	0	0	14	377
21	0	0	0	0	24	384
22	0	0	8	0	27	368
23	0	0	13	0	24	383
24	0	0	25	0	22	415
25	0	0	71	0	16	473
26	0	0	55	7	26	373
27	0	0	60	13	83	327
28	11	0	60	15	77	327
29	13	0	41	14	41	277
30	21	0	24	12	24	261
31	47	0	12	4	3	332
32	67	0	0	0	0	338
33	44	9	10	0	0	318
34	26	22	13	9	0	315
35	12	29	13	17	10	273
36	0	33	13	31	61	265
37	0	35	13	37	103	293
38	0	25	13	32	111	302
39	0	10	10	20	103	325
40	0	0	0	12	63	287
41	0	0	0	0	22	254
42	0	0	0	0	0	240
43	0	0	0	0	0	262
44	0	0	0	0	0	259
45	0	0	0	0	0	250
46	0	0	0	0	0	252
47	0	0	0	0	0	263
48	0	0	0	0	0	248
49	0	0	0	0	0	219

50	0	0	0	0	0	223
51	0	0	0	0	0	214
52	0	0	0	0	0	213

Year	1995					
Week	Scots Bay(Z8)	Trinity(Z3)	Lurcher(Z4)	Seal Island(Z6)	German Bank(Z7)	Total
1	0	0	0	0	0	192
2	0	0	0	0	0	166
3	0	0	0	0	0	177
4	0	0	0	0	0	209
5	0	0	0	0	0	226
6	0	0	0	0	0	261
7	0	0	0	0	0	282
8	0	0	0	0	0	281
9	0	0	0	0	0	266
10	0	0	0	0	0	265
11	0	0	0	0	0	265
12	0	0	0	0	0	264
13	0	0	0	0	0	263
14	0	0	0	0	0	263
15	0	0	0	0	0	262
16	0	0	0	0	0	279
17	0	0	0	0	0	281
18	0	0	0	0	0	279
19	0	0	0	0	7	284
20	0	0	0	0	14	286
21	0	0	0	0	22	282
22	0	0	8	0	29	274
23	0	0	13	0	13	294
24	0	0	19	0	14	325
25	0	0	30	0	28	281
26	0	0	40	5	65	288
27	0	0	76	13	94	348
28	9	0	67	16	15	241
29	13	0	46	14	25	264
30	21	0	26	12	9	238
31	25	0	12	4	4	279
32	24	0	0	0	0	269
33	16	9	10	0	0	270
34	13	17	13	9	0	299
35	10	25	13	21	10	278
36	0	30	14	55	32	270
37	0	29	13	50	46	252
38	0	17	13	38	82	271
39	0	10	10	24	82	308
40	0	0	0	11	43	285
41	0	0	0	0	14	267
42	0	0	0	0	0	252
43	0	0	0	0	0	263
44	0	0	0	0	0	250
45	0	0	0	0	0	245
46	0	0	0	0	0	246
47	0	0	0	0	0	246
48	0	0	0	0	0	231
49	0	0	0	0	0	222

50	0	0	0	0	0	226
51	0	0	0	0	0	217
52	0	0	0	0	0	216

Appendix K

Pascal code for calculating updated weekly total stock estimates using discretized catch data and update equations (3.3) and (3.4). Output consists of the week, the estimates of zone population for each spawning area for that week and the aggregated population total over all 15 zones for the week.

```

program update(input,output);

var h,i,j,k,l,z,sflag,yr,numqp,pl:integer;
    numq:array[1..6] of integer;
    cg:array[1..52,1..15] of integer;
    expc:array[1..6,1..13] of real;
    totalabund,denominator,tc,gtc,sum:real;
    P:array[1..10,1..10] of real;
    Q:array[1..6,1..10,1..13] of real;
    pijl:array[1..10,1..10] of real;
    pi,newpi:array[1..150] of real;
    numerator,explevel:array[1..10] of real;
    Pfile,Qfile,catchfile,afile:text;
    zoneabund:array[1..15] of real;
    ip:array[5..10,1..10] of real;

{ This program reforms continuous updating by week through the years 1991-1995. }
{ P1=11 is believed abundance level at beginning of 1991. }

begin
{Output of new probability distributions with expected population levels.}
{File preparation}
assign(Pfile,'pd10noc.dat');
reset(Pfile);
assign(Qfile,'q10.dat');
reset(Qfile);
assign(afile,'ab6b0.dat');
rewrite(afile);
assign(catchfile,'c3.bcf');
reset(catchfile);

{Input numbers of catch classes,expected absolute catch for each group of zones.}
numq[1]:= 13;
numq[2]:= 9;
numq[3]:= 7;
numq[4]:= 12;
numq[5]:= 13;
numq[6]:= 2;
for i:= 1 to 5 do expc[i,1]:= 0.0;
for i:= 2 to 13 do expc[1,i]:= 500.0*(i-2)+250.0;
for i:= 2 to 9 do expc[2,i]:= 250.0*(i-2)+125.0;
for i:= 2 to 7 do expc[3,i]:= 50.0*(i-2)+25.0;
for i:= 2 to 6 do expc[4,i]:= 500.0*(i-2)+250.0;
for i:= 2 to 13 do expc[5,i]:= expc[1,i];
for i:= 1 to 2 do expc[6,i]:= 0;
{Set expected abundance for each population level.}
explevel[1]:= 0.0;
for i:= 2 to 5 do explevel[i]:= 12.5+25*(i-2);
for i:= 6 to 10 do explevel[i]:= 125+(i-6)*50.0;

{Input Q probabilities for each class,i, of zones.}
for i:= 1 to 6 do {i=group of zones}
begin
for j:= 1 to 10 do {j=given state of zone}
begin
for h:= 1 to numq[i] do {k= catch level}
begin
read(Qfile,Q[i,j,h]);
end;
end;
end;

{Classify each zone.}
for l:= 1 to 52 do
begin
for z:= 1 to 15 do if (z=9) then cg[l,z]:= 4
                    else if (z=12) then cg[l,z]:= 6 else if (z>9) or (z=4) then cg[l,z]:= 3
                    else if (z>5) then cg[l,z]:= 1
                    else cg[l,z]:= 2;
if ((z=7) and (l>34)) or ((z=6) and (l>34)) then cg[l,z]:= 5;
end;
end;

```

```

ip{5,1}:= 0.5;
ip{6,1}:= 0.5;
ip{5,2}:= 0.35;
ip{6,2}:= 0.35;
ip{5,3}:= 0.25;
ip{6,3}:= 0.25;
ip{5,4}:= 0.15;
ip{6,4}:= 0.15;
ip{5,5}:= 0.05;
ip{6,5}:= 0.05;
for pl:= 6 to 10 do ip{5,pl}:= 0.0;
for pl:= 6 to 10 do ip{6,pl}:= 0.0;
ip{7,1}:= 0.0;
ip{8,1}:= 0.0;
ip{7,2}:= 0.15;
ip{8,2}:= 0.15;
ip{7,3}:= 0.25;
ip{8,3}:= 0.25;
ip{7,4}:= 0.35;
ip{8,4}:= 0.35;
ip{7,5}:= 0.45;
ip{8,5}:= 0.45;
ip{7,6}:= 0.5;
ip{8,6}:= 0.5;
ip{7,7}:= 0.35;
ip{8,7}:= 0.35;
ip{7,8}:= 0.25;
ip{8,8}:= 0.25;
ip{7,9}:= 0.15;
ip{8,9}:= 0.15;
ip{7,10}:= 0.0;
ip{8,10}:= 0.0;
for pl:= 1 to 6 do ip{9,pl}:= 0.0;
for pl:= 1 to 6 do ip{10,pl}:= 0.0;
ip{9,7}:= 0.15;
ip{10,7}:= 0.15;
ip{9,8}:= 0.25;
ip{10,8}:= 0.25;
ip{9,9}:= 0.35;
ip{10,9}:= 0.35;
ip{9,10}:= 0.5;
ip{10,10}:= 0.5;

for pl:= 1 to 11 do
begin
{Set given initial state probabilities.}
for i:= 1 to 150 do pi[i]:= 0.0;
for i:= 1 to 15 do pi[ $((i-1)*10)+1$ ]:= 1.0;
pi[1]:= 0.0;
pi[2]:= 1.0;
pi[3]:= 0.0;
for i:= 1 to 4 do pi[80+i]:= 0.0;
for i:= 5 to 10 do pi[80+i]:= ip[i,pl];
if (pl= 11) then begin
    pi[83]:= 0.001;
    pi[84]:= 0.002;
    pi[85]:= 0.003;
    pi[86]:= 0.061;
    pi[87]:= 0.092;
    pi[88]:= 0.15;
    pi[89]:= 0.191;
    pi[90]:= 0.50;
end;
totalabund:= 12.5; {zone 1};
for i:= 5 to 10 do totalabund:= totalabund+ pi[80+i]*explevel[i];
for yr:= 1 to 5 do

begin
{Titles section.}

```

```

writeln(afile,'Population Abundance Estimates By Week');
writeln(afile,'PopulationLevel ',pl,' Year ',yr);
writeln(afile,'Week ScotsBay(Z8) Trinity(Z3) Lurcher(Z4) SeallIsland(Z6) GermanBank(Z7) Total');

tc:= 0;
{Updating section.}
for l:= 1 to 52 do {l=week being updated}
begin
totalabund:= 0.0;
for z:= 1 to 15 do {z=zone being updated}
begin
{Read catch signal and transition probabilities.}
read(catchfile,k);
tc:= tc+expc[cg[l,z],k];
for i:= 1 to 10 do for j:= 1 to 10 do read(Pfile,pijl[i,j]);

{Calculate simulated state level.}
if (k>1) then sflag:= 0
else
begin
case z of
1: begin
if ((l>8) and (l<24)) or ((l>37) and (l<44))
then sflag:= 1
else sflag:= 0;
end;
2: begin
if (l>=22) and (l<45) then sflag:= 0
else sflag:= 1;
end;
3: begin
if ((l>=22) and (l<25)) or ((l>=30) and (l<39)) then sflag:= 0
else sflag:= 1;
end;
4: begin
if (l>22) and (l<31) then sflag:= 0
else sflag:= 1;
end;
5: begin
if (l>22) and (l<43) then sflag:= 0
else sflag:= 1;
end;
6: begin
if (l>28) and (l<42) then sflag:= 0
else sflag:= 1;
end;
7: begin
if (l>22) and (l<42) then sflag:= 0
else sflag:= 1;
end;
8: begin
if (l>27) and (l<35) then sflag:= 0
else sflag:= 1;
end;
9: begin
if (l<9) or ((l>42) and (l<49)) then sflag:= 0
else sflag:= 1;
end;
10: begin
if (l>27) and (l<33) then sflag:= 0
else sflag:= 1;
end;
11: begin
if ((l>23) and (l<29)) or ((l>32) and (l<35)) then sflag:= 0
else sflag:= 1;
end;
12,14,15: begin
sflag:= 1;
end;
13: begin
if (l>26) and (l<32) then sflag:= 0

```

```

        else sflag:= 1;
        end;
    end; {case}
    end; {If k=1.}

if (sflag=0) then
begin {Use catch as signal.}
    for j:= 1 to 10 do
        begin
            numerator[j]:= 0.0;
            for i:= 1 to 10 do numerator[j]:= numerator[j]+pijl[i,j]*pi[(z-1)*10+i]*Q[cg[l,z],j,k];
            end;

{Calculate denominator for updated probability distribution, updated probabilities.}
            denominator:= 0.0;
            for j:= 1 to 10 do denominator:= numerator[j]+denominator;

            for j:= 1 to 10 do newpi[(z-1)*10+j]:= numerator[j]/denominator;

end; {Updating procedure using signals where sflag=0.}

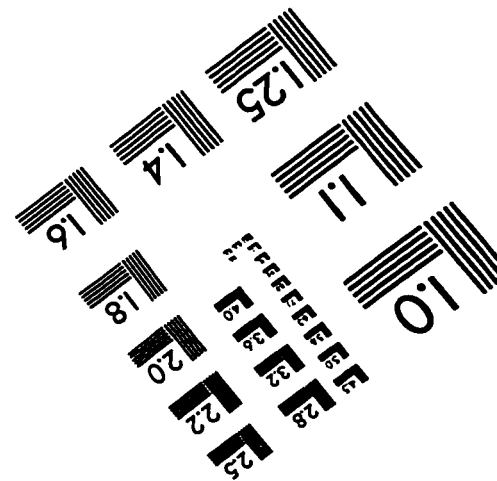
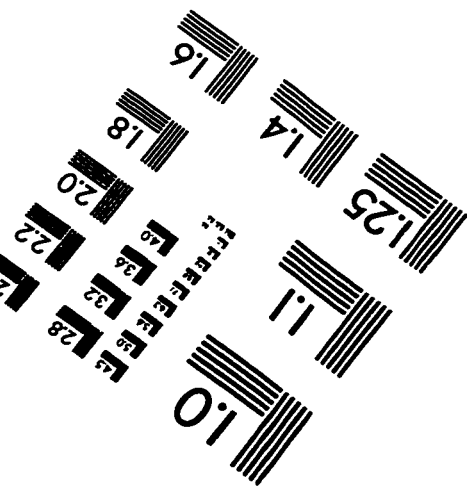
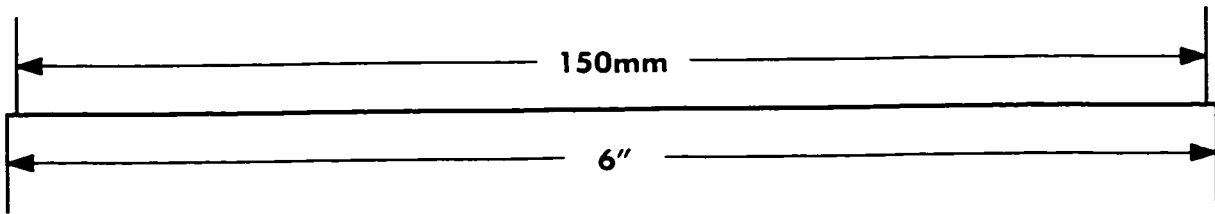
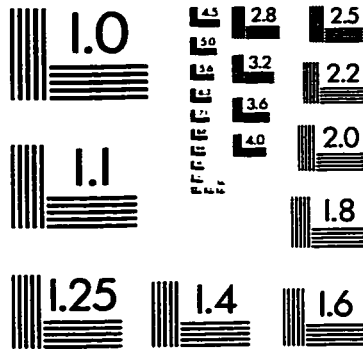
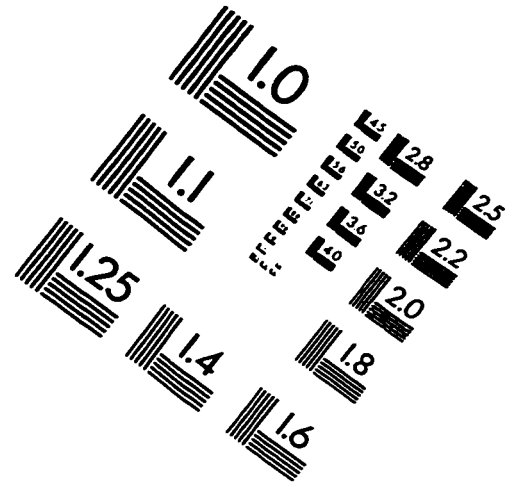
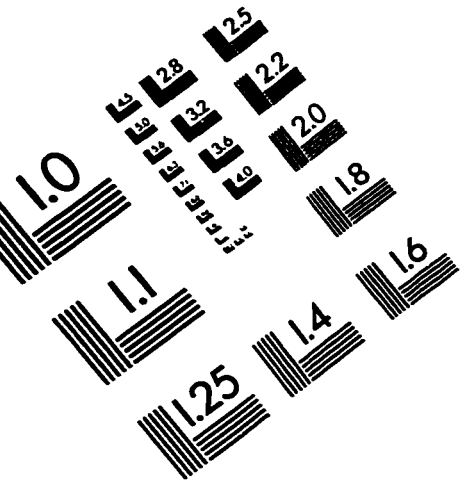
if (sflag=1) then
begin
    for j:= 1 to 10 do newpi[((z-1)*10)+j]:= 0.0;
    for j:= 1 to 10 do
        for i:= 1 to 10 do newpi[((z-1)*10)+j]:= newpi[((z-1)*10)+j]+pi[((z-1)*10)+i]*pijl[i,j];
        end;
    end; {Updating procedure that doesn't use signals when sflag=1.}

{Increment estimated total population by zone estimate.}
    zoneabund[z]:= 0.0;
    for j:= 1 to 10 do zoneabund[z]:= zoneabund[z]+newpi[((z-1)*10)+j]*explevel[j];
    totalabund:= totalabund+zoneabund[z];
    end; {zone}
    write(afile,1,'.zoneabund[8].',zoneabund[3].',zoneabund[4].');
    writeln(afile,zoneabund[6].',.zoneabund[7].',totalabund);
{Replace previous estimated probability distribution with updated estimate.}
    for j:= 1 to 150 do pi[j]:= newpi[j];
    gtc:= gtc+tc;

{End of updating section.}
    end; {Week}
    reset(Pfile);
    write(afile,');
    end; {Year.}
    reset(catchfile);
    end; {Population level.}
{Close all files prior to end of program.}
    close(afile);
    close(newpifile);
    close(Pfile);
    close(Qfile);
    close(catchfile);
    end. {program}

```

IMAGE EVALUATION TEST TARGET (QA-3)



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