PRE-SEASON PREDICTION OF SOCKEYE SALMON RUNS ON THE SKEENA RIVER

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Introduction

Sockeye Salmon (Oncorhychrus nerka) of the Skeena River (British Columbia, Canada) display a high variability in population parameters from year to year. Investigation into the mechanisms which generate these variabilities is not cnly of benefit to the biologist in understanding the living system, but is also of great importance to the fishermen and his livelihood.

It is the intent of this paper to outline the problem and to report results obtained in investigating some of the parameters of the sockeye population as part of the IIASA ecology project's case study on pacific salmon.

Before proceeding some discussion is due concerning the life history of the sockeye salmon of the Skeena river. Distinction is made for those populations of the Skeena, as they differ in some important ways from other sockeye populations. Therefore in this paper sockeye will refer to Skeena sockeye only.

Sockeye return from the sea to spawn and die in either their third, fourth, fifth, or sixth year of life. The fertilized eggs are deposited in the gravel of the stream bed or lake bottom in the late summer or autumn. The young remain in the gravel until the following spring when they emerge to take up lake residence. Seaward migration, at which time they are termed smolts, occurs in the spring either one or two years later. Return to freshwater of adult fish takes place after one to three years at sea. (Larkin & Macdonald 1968)

The problem of the Fisheries Manager is many sided. For the short run year-to-year operation of the fisheries, the task is to control fishing, which takes place in the river estuary and is directed toward the adult fish returning to spawn, in such a way as to allow enough spawners past the fishery to ensure a harvest in future years. The other side of the coin is that the manager cannot, for reasons of economic efficiency, allow more fish to escape than necessary. This tradeoff between escapement and catch would be an easy task if the number of returning fish in any given year were accurately known; this is not the case.

Pre-season Prediction

Our first attempt at pre-season prediction took the shape of a Markov chain describing the life history of a sockeye salmon(see Figure 1), (Rinaldi, Personal Communication) where:

J_1, J_2, J_3: are the first second and third years of freshwater life

O_1, O_2: are the first and second years of ocean life.

R: is the state of returning

D: is the state of death

$\beta, \gamma, \delta, \Sigma, V$: are the constant probabilities of transition between two states.

Q_t: is the index of environmental quality for for year t $o \leq Q$ $Q \leq 1$ (explained below)

$P_2(Q_t), P_3(Q_t)$: are the probabilities given as a function of Q_t

$$P_2(Q_t) = a_2 + b_2 Q_t$$

$$P_3(Q_t) = a_3 + b_2 Q_t$$

A salmon can choose from four different paths

$$4_2,\ 5_2,\ 5_3,\ 6_3$$

i.e. 5_3 means it returned after five years and spent three of those in freshwater. Now we can compute the probability of returning via any path.

i.e. $$q^i_{4_2} = \beta\ \Sigma\ P_2(Q_{i+2}) = H_1 + K_1\ Q_{i+2}$$

similarly :

$$q^i_{5_2} = H_2 + K_2\ Q_{i+2}$$

$$q^i_{5_3} = H_3 + K_3\ Q_{i+3}$$

$$q^i_{6_3} = H_4 + K_4\ Q_{i+3}$$

It can be shown that:

$$\frac{H_2}{H_1} = \frac{H_4}{H_3} = \frac{K_2}{K_1} = r = \frac{\delta V}{\Sigma}$$

now we get

$$q^i_{4_2} = H_1 + K_2\ Q_{i+2}$$

$$q^i_{5_2} = r(H_1 + K_2\ Q_{i+2})$$

$$q^i_{5_3} = H_3 + K_3\ Q_{i+3}$$

$$q^i_{6_3} = r(H_3 + K_3\ Q_{i+3})$$

Notice that r is the ratio of fish that spend three years at sea to those that spend two. Data exists which catagorises both catches and escapement so that r can be estimated.

Result: $r = 0.8$.

Eventually we can describe the population by the equation;

$$
\begin{aligned}
R_t = {} & (H_1 + K_1 Q_{t-2})\ f\ (S_{t-4}) + \\
& + (r(H_1 + K_1 Q_{t-3}) + H_3 + K_3 Q_{t-2})\ f\ (S_{t-5}) \\
& + r\ (H_3 + K_3 Q_{t-3}) f(S_{t-6})
\end{aligned}
$$

where S_t is the spawners in year t and $f\ (S_t)$ is an appropriate stock-recruitment function. The function used here was the "Ricker-type"

$$f(S_t) = g\ \alpha\ e^{-\alpha S_t}$$

by setting $\hat{H}_i = g\ H_i$, $\hat{K}_i = gK_i$

and $$h(S_t, \alpha) = \alpha e^{-\ S_t}$$

we get:

$$
\begin{aligned}
R_t & = |h(S_{t-4}, \alpha) + rh(S_{t-5}\ \alpha)|\ \hat{H}_1 \\
& = |Q_{t-2}\ h(S_{t-4}, \alpha) + r\ Q_{t-3} h(S_{t-5}, \alpha)|\ \hat{K}_1 \\
& = |h(S_{t-5}, \alpha) + r\ h(S_{t-6}, \alpha)|\ \hat{H}_3 \\
& = |Q_{t-2}\ h(S_{t-5}, \alpha) + r\ Q_{t-3}\ h(S_{t-6}, \alpha)|\ \hat{K}_3
\end{aligned}
$$

By carrying out a one dimensional search in α and a multiple linear regression for $\hat{H}_1$, $\hat{K}_1$, $\hat{H}_3$ and $\hat{K}_3$ we were able to find a minimum square error when $\alpha = 1.47$.

The assumptions of this prediction scheme were:

1. Sockeye have time invariant probabilities of choosing a life cycle strategy.
2. The environmental effect takes place in the form of stream flow at the time of seaward migration, and the probability of surviving the migration is a linear function of the stream flow.

The data used for estimating the parameters were returns and escapement for the total Skeena system for the years 1930 - 1974, and continuous stream flow data for the Babine for the years 1940 - 1972. Data for the Stuart lakes on a different river system some 200 miles away was available for the years 1929 - 1970, and by a cross correlation technique the years 1930 - 1940 for the Babine lake were estimated. The numbers used as Q_t were the summed flows of the months of May, June, and July, scaled between 0-1.

The variances of the estimate for this procedure were

S_E^2 = 0.30 million fish, S_T^2 = 0.37 million fish

R^2 = 0.28 (see Figure 2)

This procedure was then tested with constant Q which reduced the regression to two linear parameters. The variance of the estimate for this were:

S_E^2 = 0.35 million fish

S_T^2 = 0.37 million fish

R^2 = 0.13

Another approach to the prediciton problem was taken which used smolt count data rather than escapement data processed through the stock-recruitment function. A simple linear regression model was used of the form

$$R_t = b_1 f_{t-1} S_{t-1} + b_2 f_{t-2} S_{t-2} + b_3 f_{t-3} S_{t-3}$$

where

R_t = number returning in year t

f_t = stream flow in year t (same as Q above)

S_t = number of smolt counted in time t.

Results from this were:

$b_1 = 0.027$ $b_2 = 0.013$ $b_3 = 0.019$

$S_E^2 = 0.22$ million fish, $S_T^2 = 0.198$ million fish

$R^2 = 0.06$ (see Figure 4)

A second regression was performed of the form

$$R_t = b_1 S_{t-1} + b_2 S_{t-2} + b_3 S_{t-3}$$

Results were

$b_1 = 0.019$ $b_2 = 0.012$ $b_3 = 0.012$

$S_E^2 = 0.23$ million fish, $S_T^2 = 0.198$

$R^2 = 0.047$ (see Figure 5)

Using smolt counts as the input to the cycle has the advantage of eliminating the variability accrued between spawning and smolts. The disadvantage is that smolt count data only exists from 1958.

It is the opinion of this author that the prediction problem must be broken into two components:

1. Predict the number of fish to return from a given smolt season, regardless of when they return.
2. Predict when a given individual will return based upon genetic and environmental factors.

Stock - Recrutiment

Stock-Recruitment is a term used for discussing the relationship between the number of spawners and the number of their offspring which survive and return as adult fish. The stock recruitment relationship is subject to great stochastic variation (see Figure 6).

In order to improve our predictions of returns (here returns means all the fish that return from a spawning no matter at what age) it is necessary to elucidate factors which affect survival at various stages in the life history. Survival can be looked at as having two components. One is a linear factor, meaning that a population in an unlimited environment environment has a probability of surviving to the next stage in the life process.

i.e. $$N_{t+1} = a_t N_t$$

The other component is density dependent and is strongly influenced by high densities i.e.:

$$N_{t+1} = a_t N_t - b_t N_t^2$$

Some evidence for the density dependent type of survival function has been found by this author (see figure 6). Here survival rate means:

$$\frac{N_{t+1}}{N_t}$$

NB: t+1 is the time of return regardless of the age of return.

This relationship will have a good test with perhaps disasterous effects in the return of 1975 and 1976. In 1973 a new enhancement program was initiated for the Skeena sockeye. Hatchery channels were used to practically double the number of smolts leaving the river.

Conclusion

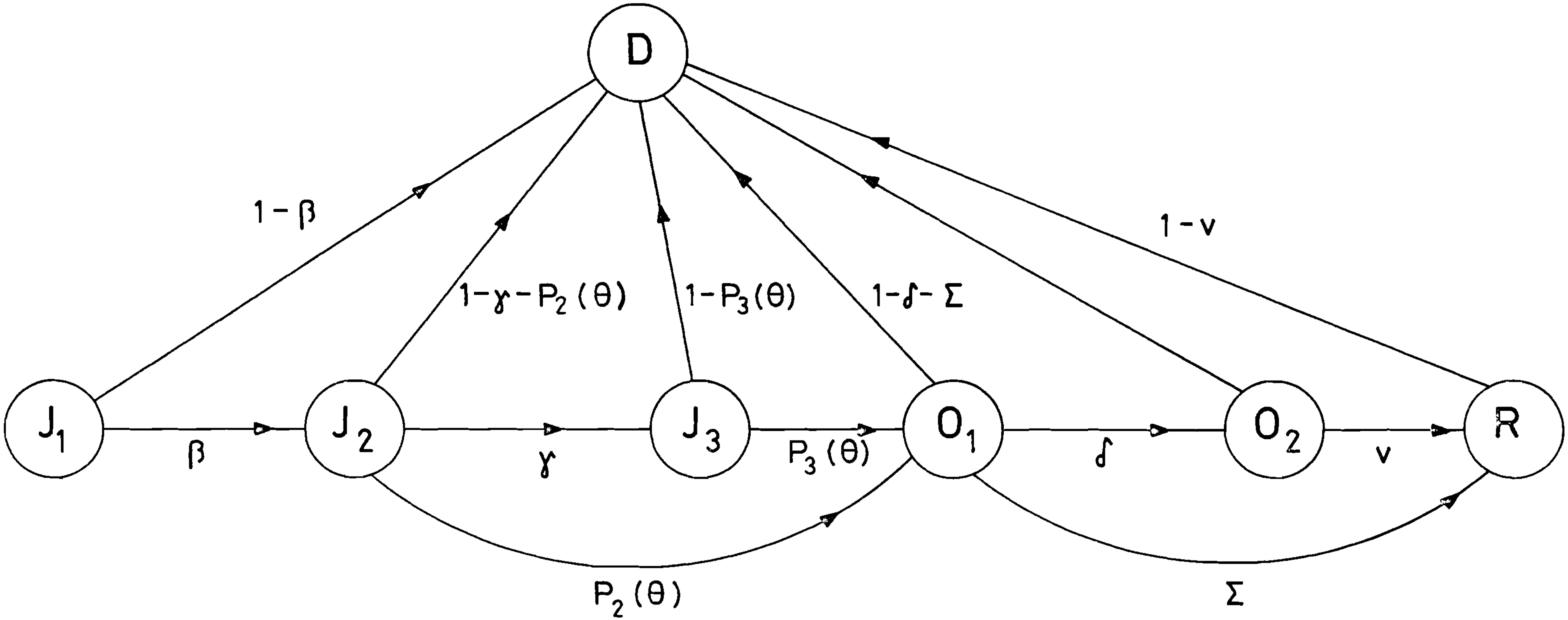
The methods of prediction reported here have shown promise even though there is a lack of accuracy. It seems reasonable to say that stream flow at the time of Seaward migration may play an important part in smolt survival. Better flow data more closely associated with the mouth of the river would indicate more conclusively whether there is any association with survival.

It is the opinion of this author that the general form of the Markov model is very useful. The assumption of constant transition probabilities: $\beta\gamma$ (etc.) would seem to be a far from accurate hypothesis, Although the mean of the r was 0.8 the variance was greater than 2. Hence insight into the mechanisms which affect the r's through time is needed to increase the accuracy of prediction. Some methods for predicting the r's and incorporating them into the general prediction scheme are being investigated, but at this time no results have been obtained.

As for the second model for prediction, it was possibly too simplistic. It has been shown that there is a strong density dependent relationship between smolts and returning adults. At present work is in progress to incorporate this into the regression model. It is my conclusion that elucidation of the mechanisms, both genetic and environmental, which determine the age of return and the life strategy chosen would greatly improve the prediction task.

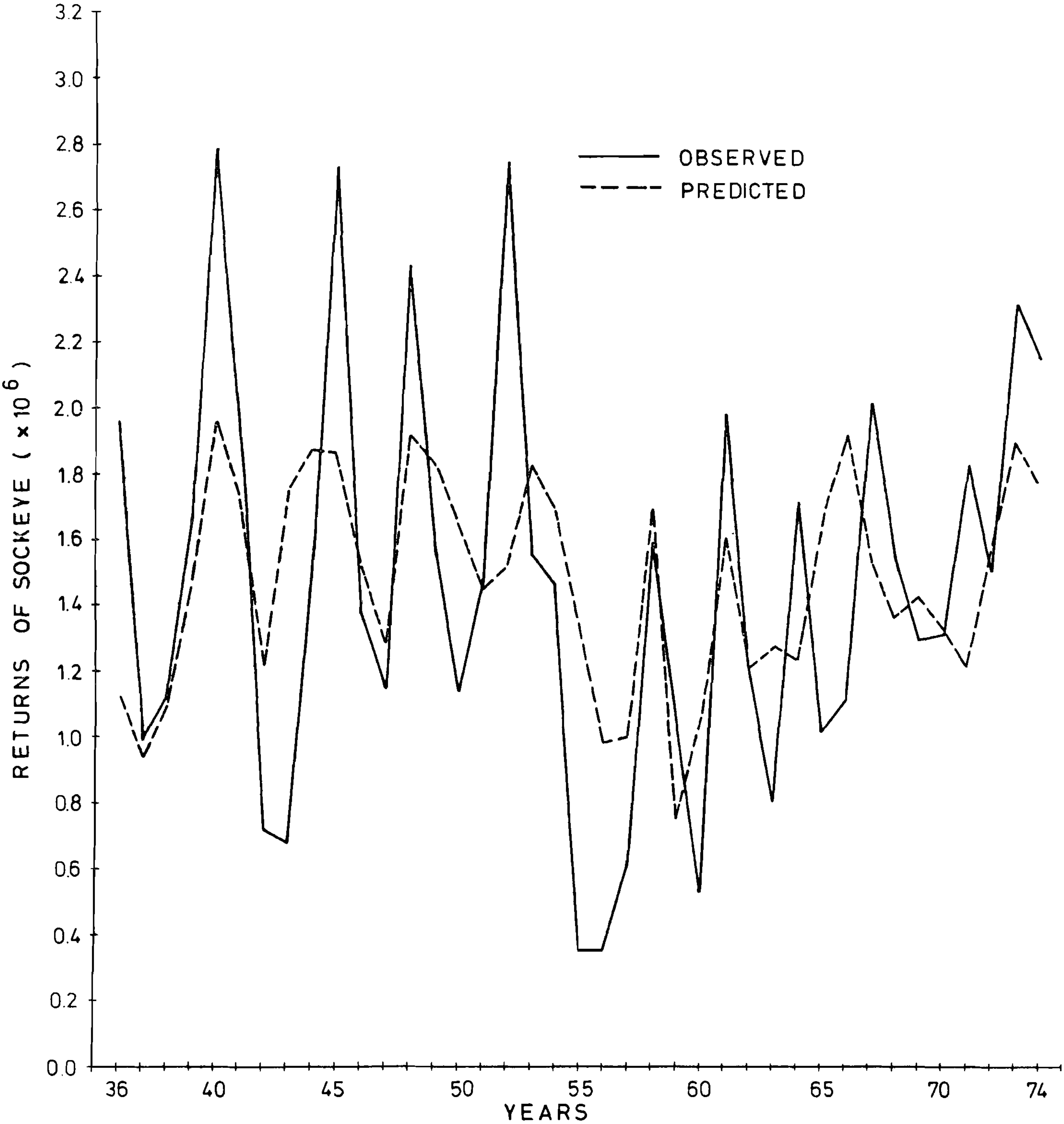
REFERENCE

LARKIN, P.A., McDONALD, J.G. 1968. "Factors in the Population of the Sockeye Salmon of the Skeena River", J. Anim. Ecol. 37, 229 - 258.



MARKOV CHAIN OF SOCKEYE LIFE HISTORY

FIGURE 1



OBSERVED
PREDICTED
RETURNS OF SOCKEYE (x 10^6)
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
36
40
45
50
55
60
65
70
74
YEARS

FIGURE 2

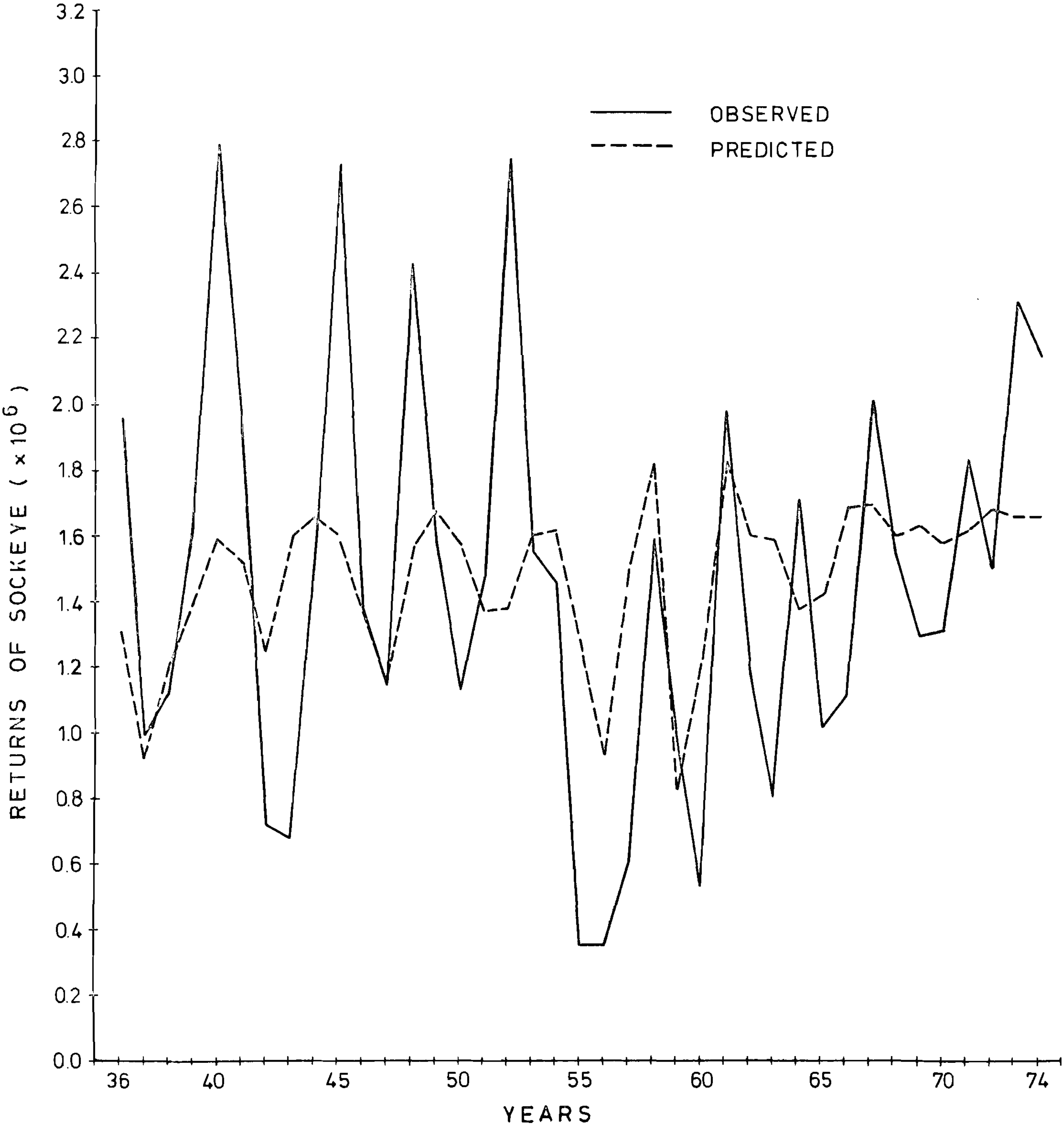
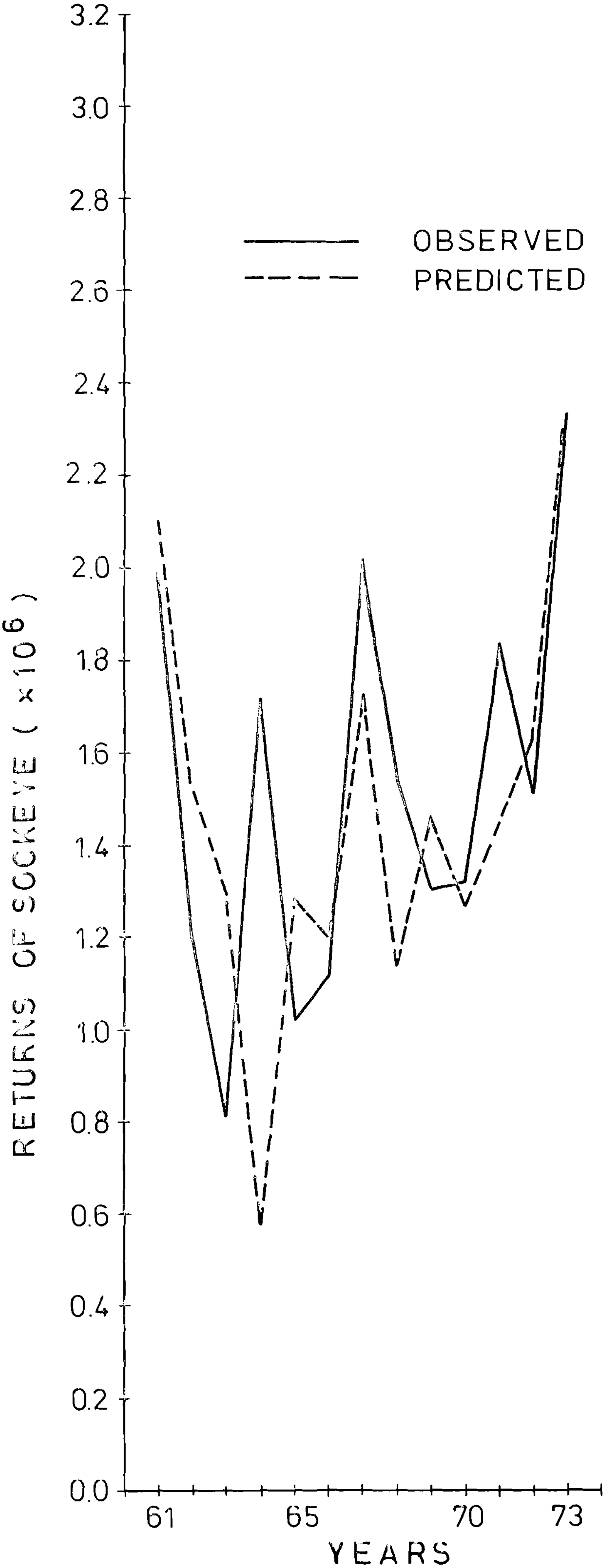

OBSERVED
PREDICTED
RETURNS OF SOCKEYE (× 10⁶)
YEARS
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
36
40
45
50
55
60
65
70
74

FIGURE 3



OBSERVED
PREDICTED
RETURNS OF SOCKEYE (×10^6)
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
61
65
70
73
YEARS

FIGURE 4

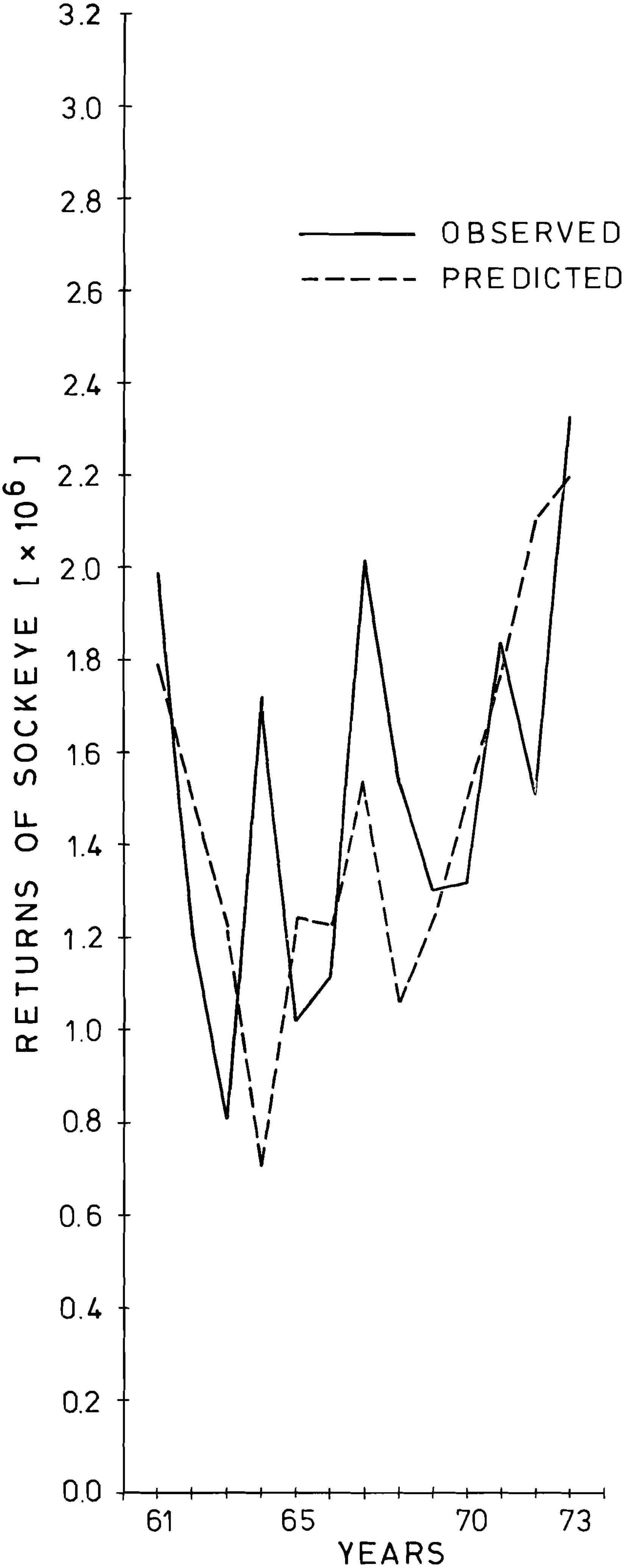

OBSERVED
PREDICTED
RETURNS OF SOCKEYE [× 10^6]
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
61
65
70
73
YEARS

FIGURE 5

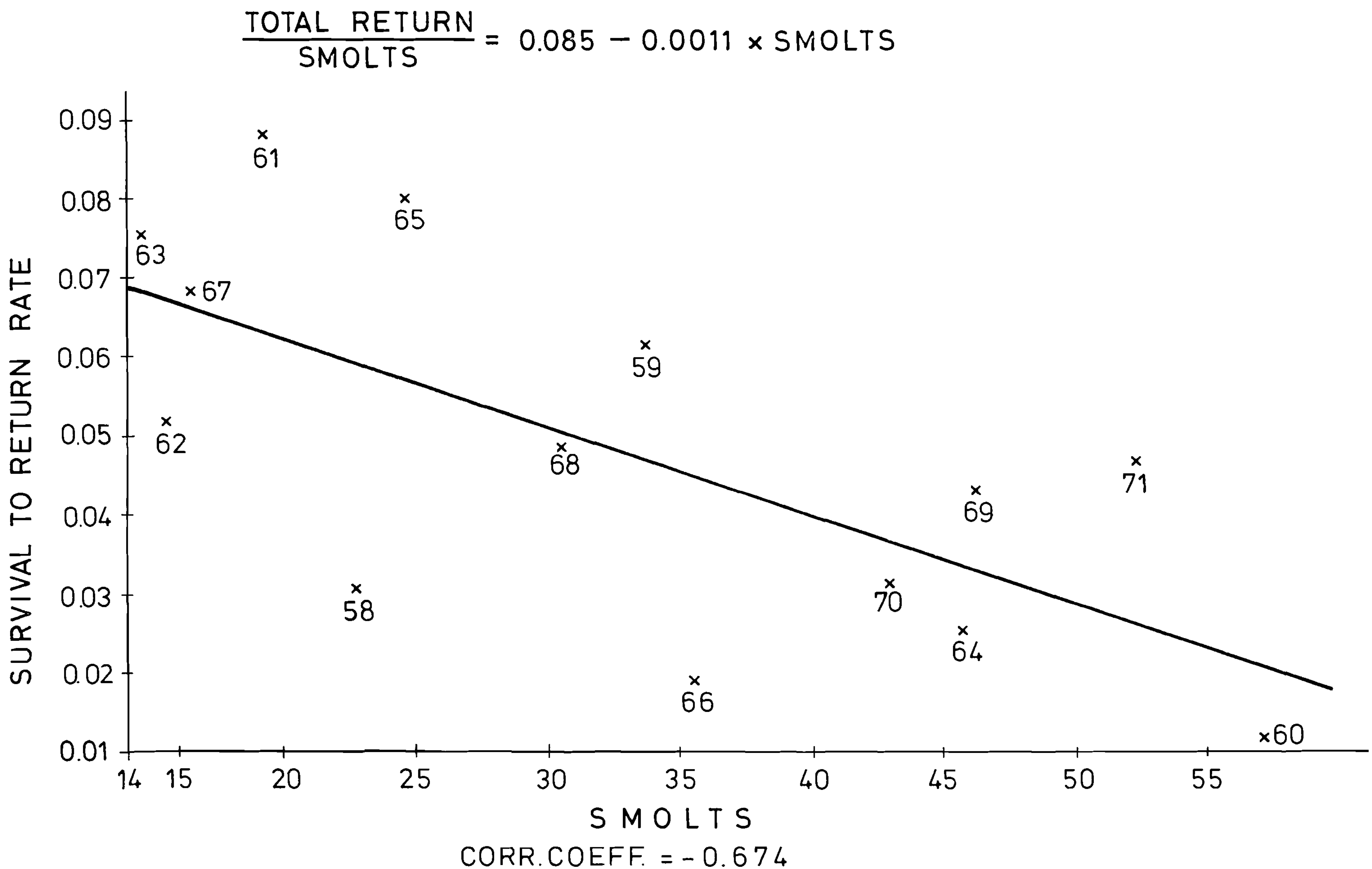

TOTAL RETURN / SMOLTS = 0.085 − 0.0011 × SMOLTS
SURVIVAL TO RETURN RATE
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
14
15
20
25
30
35
40
45
50
55
61
65
63
67
59
62
68
71
69
58
70
64
66
60
SMOLTS
CORR.COEFF. = -0.674

FIGURE 6