

INTEGRATING KNOWLEDGE TO PREDICT SPATIAL DYNAMICS OF
HERRING SHOALS USING AN EXPERT SYSTEM

by

STEVEN MACKINSON

B.Sc., Royal Holloway College, University of London, 1991

M.Sc., King's College, University of London, 1992

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES

Department of Resource Management and Environmental Studies

Fisheries Centre

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

September 1999

© Steven Mackinson, 1999

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Resource Management & Environmental Studies

The University of British Columbia
Vancouver, Canada

Date 13th October 1999

Abstract

By modifying and adapting their behaviour, herring display the remarkable plasticity required to succeed in a changing biological and physical environment. The basis of adaptation lies in decisions of individual fish, that make second to second evaluations of possible trade-offs, deciding accordingly whether to join, leave or stay with a shoal. Such actions are manifest as changes in the structure, dynamics and distribution of shoals; facets which for many of the world's pelagic stocks have considerable importance to central issues in fisheries management including stock structure, stock assessment, resilience and harvest control. Since fisheries generally operate within the meso-scale realm (100's m - 10's km, hour-weeks), descriptors of meso-scale spatial dynamics of fish shoals are critical diagnostics for management. The meso-scale wild studies detailed in this thesis describe spatial pattern of herring shoals using a simple quantitative index, termed the 'cluster ratio', that links scales of distribution pattern among shoals. It can be used to compare shoal clustering pattern for surveys made at different places and seasons.

Despite recent spatial dynamics studies, much of our understanding of fish behaviour and distribution remains qualitative or uncertain. A model is presented in this thesis that attempts to bridge existing gaps in our basic understanding of the biological and ecological mechanisms underpinning behavioural responses of herring, and how these govern spatial dynamics of shoals. The approach combines two fundamental sources of information: (i) 'hard data' from fieldwork and published sources; (ii) 'practical knowledge' from interviews with experts and fishery professionals including fishers, fishery managers, scientists and First Nations people.

The model, CLUPEX, is developed in the framework of an expert system and utilises fuzzy logic to capture and integrate scientific and local knowledge in the form of heuristic rules. Using input pertaining to biotic and abiotic environmental conditions, CLUPEX uses the rules to provide quantitative and qualitative predictions on the structure, dynamics and meso-scale distribution of shoals of migratory adult herring during different life stages of their annual life cycle. Predictions are generalised to two different herring species and may be used as input to harvest models, to examine the impacts of shoal structure and distribution on management of herring fisheries. An important feature of the model is that predictions constitute testable hypotheses on which to base future experiments and field observations. Test predictions correspond well with observed shoal patterns, although accuracy for specific circumstances may be limited by the resolution of the knowledge. However, by adding specific local knowledge and adjusting weighting parameters, CLUPEX can be adapted to provide more accurate and precise predictions. The user interface combines hypertext and an explanation facility that is fully cross-referenced to a database, to provide an intuitive and transparent feel rarely found in more traditional analytical models.

TABLE OF CONTENTS

Abstract	ii
Table of contents	iii
Table headings	vi
Figure captions	vii
Acknowledgements	x
 Chapter 1. Introduction and overview	 1
1.1 The 'Nature' of Herring	1
<i>Population characteristics and herring fisheries</i>	1
<i>Shoaling and schooling habit</i>	2
<i>Evolution and ecological functions of shoaling behaviour</i>	4
1.2 Instability of Herring Fisheries	7
1.3 Ecological importance	10
1.4 Thesis outline	12
<i>Rationale and objectives</i>	12
<i>Methods - Expert systems and fuzzy logic</i>	13
<i>Structure</i>	17
 Chapter 2. Herring shoals in the wild	 19
<i>Data considerations and statistical methods</i>	19
2.1 Cross-scale observations on structure, distribution and behavioural dynamics of ocean feeding Norwegian spring spawning	20
INTRODUCTION	20
MATERIALS AND METHODS	22
RESULTS	27
LARGE MESO-SCALE OBSERVATIONS	27
<i>School structure characteristics</i>	27
<i>Spatial distribution pattern</i>	30
<i>Spatial distribution by size</i>	32
<i>Diurnal temporal variation in pattern and distribution</i>	32
SMALL MESO-SCALE OBSERVATIONS	34
<i>Behavioural dynamics</i>	34
DISCUSSION	35
 2.2 Pattern and variation in structure and distribution of pre-spawning Pacific herring (<i>Clupea harengus pallasii</i>) shoals in two regions of British Columbia	 40
INTRODUCTION	40
MATERIALS AND METHODS	41
RESULTS	42
SHOAL STRUCTURE AND DISTRIBUTION	43
DIURNAL CHANGES	49
TEMPORAL CHANGES IN RELATION TO MATURATION	50
OBSERVATIONS ON PREDATORS AND FEEDING	55
DISCUSSION	56

Chapter 3. Information on herring behaviour and shoal structure, dynamics and distribution	60
3.1 Introduction	60
3.2 Field studies on herring	65
INTERNAL MOTIVATIONAL	66
<i>Seasonal changes in motivation</i>	66
INTERNAL BIOLOGICAL	67
<i>Maturation</i>	67
<i>Stock size and age structure</i>	68
EXTERNAL BIOLOGICAL	69
<i>Predators</i>	69
<i>Food</i>	70
<i>Inter-specific interactions</i>	70
EXTERNAL ABIOTIC	70
<i>Light/ Time of day</i>	70
<i>Oceanographic conditions/ physical features</i>	71
<i>Currents and water depth</i>	72
<i>Weather</i>	72
<i>Vessel disturbance</i>	73
3.3 Experimental behavioural studies	73
<i>Predators</i>	73
<i>Food</i>	74
<i>Light</i>	75
<i>Sound</i>	76
3.4 Summary	76
Chapter 4: Local knowledge on herring	77
4.1 Introduction	77
4.2 Interview selection and technique	78
4.3 Responses	80
4.4 Discussion	81
Chapter 5. An Adaptive Fuzzy Expert System for Predicting Structure, Dynamics and Distribution of Herring Shoals (CLUPEX)	84
5.1 Introduction	84
5.2 Model development - methods and approach	84
<i>Forming functional relationships using rules</i>	85
<i>Relative influence of attributes - hierarchy and trade-offs</i>	87
<i>Seasonal changes in internal motivation</i>	88
<i>Predicting structure, dynamics and distribution</i>	89
5.3 Operation and explanation facility	91
<i>Example 1: Overwintering Pacific herring</i>	92
<i>Example 2: Ocean feeding Norwegian spring spawning herring</i>	129

5.4 Results and sensitivity analysis	136
<i>General predictions</i>	136
(i) Diurnal changes in overwintering Pacific herring	136
(ii) Ocean feeding Norwegian spring spawning herring during daytime over a range of food and predator abundance's.	139
iii) Seasonal changes in Pacific herring	143
<i>Comparison with new data -model validation</i>	148
<i>Robustness and sensitivity analysis</i>	151
5.5 Discussion	157
 Chapter 6. Applications and Implications	 161
6.1 Introduction	161
6.2 Generating meso-scale distribution pattern of herring shoals	163
METHODS	165
<i>Model parameters and specification</i>	165
<i>Re-sampling scheme</i>	168
<i>Additional features under development</i>	170
Adding habitat structures	170
Evaluation and sensitivity criteria	171
RESULTS	171
<i>Seasonal changes in shoal distribution pattern</i>	171
<i>Effects of error-interval on shoaling pattern</i>	179
<i>Effects of re-sampling gamma distributions</i>	180
DISCUSSION	182
6.3 Implications to harvest control in fisheries on shoaling species	184
SIMPLE CONCEPTUAL MODEL OF A HERRING SEINE FISHERY	184
<i>Behaviour of fishers</i>	184
<i>Herring behaviour</i>	186
<i>Evaluation of model fishery</i>	186
DISCUSSION	188
 Chapter 7. Summary and concluding comments	 191
CONCLUSION	198
 References	 199
Appendices	214
Appendix 2.1.1 Acoustic settings	214
Appendix 2.1.2 School tracking	214
Appendix 2.1.3 Descriptions of behavioural events (from Pitcher et al.1996)	215
Appendix 2.1.4 Institute of Marine Research biology codes for fish data	215
Appendix 5.1 Instructions on operating CLUPEX	216
Appendix 5.2 Definitions of fuzzy variables used as input to CLUPEX	227
Appendix 5.3 Propagation of confidence	228
Appendix 5.4 Input attribute values for general prediction tests	229
Appendix A: CD-ROM - CLUPEX and Knowledge-Base	234

TABLE HEADINGS

Table 1.1 Definitions of the ways in which fish shoals counter predator attacks.	5
Table 2.1 Comparison of school distribution parameters.	32
Table 2.2 Observed and expected frequencies of occurrence of schools of certain sizes as nearest neighbours.	32
Table 2.3 Differences in diurnal distribution pattern.	33
Table 2.4 Classification of shoal shapes.	41
Table 2.5 Comparison of maturity stages of BC roe-herring industry and those described by Hay (1985).	43
Table 2.6 Statistical summary for 8 biometric parameters of herring shoals.	44
Table 2.7 Observed and expected (values in brackets) occurrence of different sized neighbour shoals in the CC.	48
Table 2.8 Summary table of diurnal changes in structure and distribution of shoals.	49
Table 2.9 Regression analysis results of changes in biometric shoal parameters over time.	54
Table 3.1a Summary table of relationships between attributes and descriptors used in CLUPEX.	62
Table 3.1b Descriptor and attribute inter-relations used in the model.	64
Table 3.2 Categorisation of shoal descriptors discussed in literature.	61
Table 5.1 Running table: calculation of confidence for each descriptor.	95
Table 5.2 Summary table of rules and facts used predicting structure, dynamics and distribution of overwintering Pacific herring shoals.	125
Table 5.3 Summary table of rules and facts used in predicting structure, dynamics and distribution of ocean feeding Norwegian spring spawning herring shoals.	132
Table 5.4 Qualitative descriptors of predictions for diurnal changes.	139
Table 5.5 Qualitative descriptors of predictions for ocean feeding Norwegian spring spawning herring.	144
Table 5.6 Qualitative prediction of seasonal changes in Pacific herring.	146
Table 5.7 Predicted qualitative temporal changes in pre-spawning Pacific herring shoals.	150
Table 5.8 Observed temporal changes of shoal structure and distribution. Spiller channel, central coast, B.C. March 1998.	151
Table 5.9 Rules classified in 12 groups according to their utilisation in 90,000 random runs of the complete system.	153
Table 5.10 Table of attribute utilisation groups in 90,000 random runs of the complete system.	154
Table 5.11 Remaining rules at each rule removal stage of for 2 formal relaxation approaches.	155
Table 6.1 Gamma distribution scale and shape parameters from fits to empirical data.	169
Table 6.2 Gamma distribution parameters used for seasonal simulations.	171

Table 6.3 Quantitative descriptors of seasonal changes in Pacific herring used in the visualisation model.	172
Table A 5.4.1 Input values for diurnal changes in overwintering Pacific herring.	229
Table A 5.4.2 Input values for ocean feeding Norwegian spring spawning herring.	230
Table A 5.4.3 Input parameters for seasonal changes in Pacific herring.	231
Table A 5.4.4 Input parameters for comparison with real data on pre-spawning Pacific herring.	233

FIGURE CAPTIONS

Figure 1.1 Scheme of the mechanism of aggregation explaining different types of cluster observed in Mediterranean Sea.	4
Figure 1.2 Sustainable yield upon fishing effort curves for the three models.	9
Figure 1.3 Biomass changes predicted by three bioeconomic models during non-cooperative behaviour of fishers.	10
Figure 1.4 Schematic of an Expert System.	15
Figure 1.5 Fuzzy sets on the fuzzy variable 'height'.	16
Figure 2.1 Recordings of herring schools by the (a) EK-500 echosounder (b) SIMRAD SA950 sonar.	24
Figure 2.2 Meso-scale mapping of herring schools.	25
Figure 2.3 Schematic representation of hypothetical patterns of school clustering.	26
Figure 2.4 Distribution of herring schools in the Norwegian Sea.	27
Figure 2.5 Size class frequencies and proportional contribution to total relative size of echosounder recorded schools.	28
Figure 2.6 Frequency distribution of school area.	29
Figure 2.7 Frequency distribution of school relative density.	29
Figure 2.8 Distribution of NND.	30
Figure 2.9 Cluster analysis tree, derived from a matrix of distances between schools recorded by echosounder.	31
Figure 2.10 Distribution of cluster coefficient values.	31
Figure 2.11 Relationships between average nearest neighbour distance, mean average inter-school distance and school size for echosounder data.	33
Figure 2.12 Diurnal changes in vertical distribution recorded by echosounder.	34
Figure 2.13 Diurnal depth of distribution of sonar recorded schools.	34
Figure 2.14 Distribution of behaviour events.	35
Figure 2.15 Behavioural event intervals of tracked schools.	36
Figure 2.16. Calculation of mean NND and mean \overline{ISD} .	42

Figure 2.17 Distribution of shoal frequency and biomass in 5 size categories.	44
Figure 2.18 Distribution of major concentrations of herring shoals in the Central Coast.	45
Figure 2.19 Distribution of major concentrations of herring shoals in the Strait of Georgia.	46
Figure 2.20 Occurrence of shoal shapes.	46
Figure 2.21 Association of herring shoals in SoG with dips in seabed.	47
Figure 2.22 Echosounder recording of daytime small-medium sized, pelagic, spherical shaped shoals.	47
Figure 2.23 Size of adjacent shoals recorded on cruise track SoG and CC.	48
Figure 2.24 Diurnal differences in relative depth of shoals.	50
Figure 2.25 Temporal changes in maturation (% roe yield from females) in SoG (1997) and CC (1998).	51
Figure 2.26 Frequency distributions of herring samples taken on dates through test sample period.	52
Figure 2.27 Lower and upper quartiles of size range from test samples in SoG.	53
Figure 2.28 Distribution of herring shoals in Baynes sound (SoG) on 3rd March 1997.	54
Figure 2.29 Changes in distribution pattern of shoals in Spiller channel during maturation.	55
Figure 4.1 Combining sources of data.	78
Figure 4.2 Comparison of descriptors and attributes derived from interviews and literature sources that were later used in forming rules.	82
Figure 5.1 Membership functions of fuzzy sets on the fuzzy variable 'Current Strength'.	86
Figure 5.2 FAM map associating stock size and age structure with spatial range occupied by the stock.	86
Figure 5.3 Output fuzzy sets for shoal size used in de-fuzzification.	90
Figure 5.4 Linkages between facts and rules during an example run for overwintering Pacific herring.	93
Figure 5.5 Location map used to derive which herring species the user is interested in.	94
Figure 5.6 General characteristics input screen.	95
Figure 5.7 Input of predator species.	102
Figure 5.8 Abundance of aquatic predators input screen.	103
Figure 5.9 Input screen for biophysical factors.	116
Figure 5.10 Vessel avoidance input screen.	118
Figure 5.11 Fish size composition input screen.	118
Figure 5.12 Physical topography/ substrate input screen.	119
Figure 5.13. Results screen with hypertext and explanation of fuzzy predictions.	123
Figure 5.14 Rules used in predicting shoal size for overwintering Pacific herring example.	124
Figure 5.15 De-fuzzification calculation for quantitative prediction of shoal size for overwintering Pacific herring example.	124

Figure 5.16 Summary output screen of quantitative predictions.	125
Figure 5.17 Input screen for food and feeding attributes asked during ocean feeding scenario.	129
Figure 5.18 Fish direction screen asked of user.	130
Figure 5.19 Competition for other species input screen.	130
Figure 5.20 Input screen for bird distribution and query of 'Why?' the question is being asked.	131
Figure 5.21 Input screen for water temperature regime.	131
Figure 5.22 Predicted 'typical' diurnal changes in herring shoal structure and distribution.	138
Figure 5.23 Predicted changes in shoal structure, dynamics and distribution of ocean feeding Norwegian spring spawning herring.	141
Figure 5.24 Quantitative predictions of seasonal changes in herring shoal structure, dynamics and distribution.	145
Figure 5.25 Predicted and observed structure and distribution of herring shoals.	149
Figure 5.26 Utilisation of rules, qualifiers and variables during 90,000 random test runs of the complete system.	151
Figure 5.27 Comparison of predictive capability of model after removal of rules.	156
Figure 5.28 Information loss after systematic removal of rules using 2 approaches.	157
Figure 6.1 Simple stock-size-dependent harvest strategies.	162
Figure 6.2 British Columbia roe-herring fishery catch vs. quota since inception of fixed harvest rate policy.	162
Figure 6.3 Schematic of integrated model combining CLUPEX and ShoalPattern models.	164
Figure 6.4 Measurement of mean NND based on observation.	166
Figure 6.5 Measurement of mean \overline{ISD} based on observation.	166
Figure 6.6 Use of NND and ICD parameters in the ShoalPattern model.	167
Figure 6.7 Gamma distribution fits to empirical data.	169
Figure 6.8 Visualisations of predicted seasonal structure and meso-scale distribution of herring shoals	173
Figure 6.9 Effects of error interval on shoaling pattern.	180
Figure 6.10 Shoal patterns from re-sampling gamma distributions.	181
Figure 6.11 Conceptual model of linkages between shoaling and fishing dynamics in a herring seine fishery.	187
Figure 6.12 Hypothetical performance curve.	188
Figure 6.13 Summary of decisions on harvest control tactics in British Columbia roe herring gillnet fishery.	190
Figure 7.1 A herring's fitness depends on several conflicting demands.	191

Acknowledgements

I am very grateful and extend by sincere thanks to; Bill Wilson (skipper F/V 'Kynoc') for his patience, co-operation and wealth of knowledge that was readily supplied during Pacific surveys; Bill's crew (Chop, Al, Corrie, Timmy, Grant) for making me welcome, help and constant humour; Lorena Hamer (DFO) for making my participation in BC herring surveys possible and also for supplying charter vessel survey data; Norwegian colleagues Leif Nøttestad, Ole Arve Misund and Anders Fernö, from the Institute of Marine Research and the University of Bergen for invitation to participate in field studies in the Norwegian Sea and collaboration on a paper based on Chapter 2. Special thanks to my friend and colleague Leif, for inspiration, enthusiasm and fly fishing; Sylvie Guénette for processing acoustic data used in Chapter 2; to all those who participated in interviews; to my supervisor Tony Pitcher, for introducing me to herring, help in teaching me to write and support throughout; my supervisory committee, Dr. Daniel Pauly for having heard of expert systems, Dr. Daniel Ware (DFO) for encouragement, opinions, and financial support; Nathaniel Newlands for many fruitful discussions plus programming and mathematical talents contributed in Chapter 6; to Dr. John Meech for his guidance in the fuzzy world; Les Lavkulich, for unfaltering support and his perfect guidance on my path and those of others; my friend, fishing partner and colleague, Marcelo, for necessary diversions; my wife Caroline, for steadfast support through all and ensuring my connection to reality; my family for everything; the International Council of Canadian Studies for support of a Commonwealth Scholarship.

Chapter 1

Introduction and Overview

'Now up git the herrin',
The King O' the sea.
Says he to the skipper,
"Look under your lee."

Chorus: For its windy old weather, stormy old weather.
When the wind blow we'll all be together.'

(Traditional – 'The Haisbro Light Song')

This thesis sets out to demonstrate a method by which knowledge of behavioural ecology can be used to predict spatial dynamics of herring shoals. Since the precise factors that determine changes in structure, dynamics and meso-scale distribution of herring shoals are not well understood, multiple sources of knowledge are integrated in the framework of a fuzzy logic expert system. Such work is necessary to develop spatially explicit predictive models needed for management.

1.1 The 'Nature' of Herring

Population characteristics and herring fisheries

Species

Of the small pelagics, clupeoids are world-wide, economically the most important single fish group (Whitehead, 1985). The suborder Clupeiodei has an evolutionary history back to the Cretaceous and contains more than 330 species in 80 genera. The two most ubiquitous and commercially important sub-species are the Pacific herring (*Clupea harengus pallasii*) and Atlantic herring (*Clupea harengus harengus*) (Blaxter, 1985). Together they constitute about 8% of world clupeoid catches; with landings of Atlantic herring being greater than those of Pacific.

Svetovidov (1963) divided herring into 5 subspecies according to their distribution:

1. *Clupea harengus harengus* - North Atlantic and Barents sea;
2. *Clupea harengus pallasii* - Pacific arctic and adjoining seas;
3. *Clupea harengus membras* - Baltic sea;
4. *Clupea harengus pallasii maris-albi* - White Sea area;
5. *Clupea harengus pallasii suworowi* - Chesha Bay area.

Range

The distribution and biomass of herring is telling of their evolutionary success. Atlantic herring are distributed widely and, in order of size, the major historical stocks include; Norwegian spring spawners (Dragesund et al. 1980), North Sea (Saville and Bailey, 1980), Georges bank (Anthony

and Waring, 1980), Icelandic (Jakobsson, 1980), Baltic (Reichlin and Bormann, 1980) and Celtic Sea (Molloy, 1980).

Pacific herring range from Korea to northern Kamchatka on the Asian coast, and from southern California to the Mackenzie River Delta on the North American coast (Hart, 1973; Blaxter, 1985). The greatest abundance and most commercially important stocks extend from Washington along the coast of British Columbia to Southeast Alaska.

Variability

Historically, herring fisheries in both the Atlantic and Pacific have shown periods of boom and bust, associated with the expansion and collapse of stocks (Dragesund et al. 1980; Hourston, 1980; Burd, 1990). Reliance on strong year classes is in part responsible for the 'boom and bust' nature of herring and other small pelagic fisheries.

Like all clupeoids, even in the absence of fishing pressure, herring are subject to great natural variations in abundance resulting from large fluctuations in recruitment success (Baumgartner et al. 1992). Various hypotheses (reviewed by Grosse and Hay, 1988) seek to explain this variability, and include: environmental influence during late larval-early juvenile stages (Anthony and Fogarty, 1985; Winters et al. 1985; Stocker et al. 1985), long term climate change (Kawasaki, 1992; Ware, 1990; Mysak et al. 1982), and predator-prey interactions (Walters et al. 1986; Ware, 1990).

Shoaling and schooling habit

Definitions

Formation of close, intrinsically determined social groups, or shoals (*sensu* Pitcher, 1983), is standard behaviour in herring. Most often, they perform schooling behaviour, whereby individuals within a shoal present a mutual attraction, swim in parallel and perform co-ordinated, synchronised behaviours. The school is typically a temporary gathering of individuals, usually of a single species, a single length class and a single biological stage (GEOSPACE group¹, 1993). The term 'school' is sometimes used to cover both shoaling and schooling phenomena, but here the terms are used according to the above definitions. Furthermore, the term 'aggregation' is used here in the context of individual fish, and thus is the same practical unit as the shoal (although aggregations are generally considered to be extrinsically driven). Close groups of shoals or schools are termed clusters.

Behaviour studies

Description of schooling behaviour and studies on the mechanics of schooling, formed the focus for early pioneering studies on shoaling fish (e.g. Parr, 1927; Welty, 1934; Keenleyside, 1955).

¹ GEOSPACE group, Montpellier, France: a working group studying the gregarism of pelagic species through acoustic data.

Understanding the functions of schooling behaviour in an ecological context became the next research focus (Keenleyside, 1955; Brock and Riffenburgh, 1960; Breder, 1967; Radakov, 1973) and continues to form the foundation of many studies (see Pitcher and Parrish, 1993 for review). Most recently, a broader approach has been directed to understanding the spatio-temporal nature of shoaling and schooling behaviour and its consequences for the resistance and resilience of pelagic fish stocks to fishing (e.g. Paloheimo and Dickie, 1964; Clark, 1974; Ulltang, 1980; Beverton, 1990; Pitcher, 1997).

Shoal structure

Physiological and behavioural studies have identified that both the acoustico-lateralis system and visual cues are important in shoal maintenance (Pitcher et al. 1976; Partridge and Pitcher 1980; Blaxter and Hunter, 1982). The organised internal structure of fish shoals is not rigid (Partridge et al. 1980), shoal structure and cohesiveness changing as a consequence of difference of behaviour of individuals within the shoal. Geostatistical analysis of the spatial structure within individual schools of Atlantic herring has revealed the existence of patches (Conan et al. 1988) and, variations in packing density, including vacuole regions, have been noted in several other studies (Floen et al. 1991; Gerlotto et al. 1994; Fréon et al. 1992; Misund 1993a).

Fréon et al. (1992) proposed a 'compression/stretching and tearing' hypothesis of aggregating behaviour as a mechanism to account for the internal dynamics and spatial heterogeneity observed within schools. The hypothesis compares a school to a sponge where the holes are vacuoles and the flesh is a continuum of fish. Compressing/stretching behaviour concerns mainly the description of fish inside the continuum. In an unstressed situation the distance may be large and polarisation low. In a stressed situation, the sponge presses in at the sides as interfish distance is reduced to a minimum. As individual exploratory behaviour starts to occur, the fish continuum stretches, and as individuals chose which side to move to maintain desired interfish distance, tearing occurs and a vacuole appears. The authors note that, since the school is travelling, the comparison with a sponge is limited because in fact the vacuoles are not moving with the shoals, rather it is more like a river flows around rocks (Fréon et al. 1992). The 'sponge' hypothesis complements the theory of the dynamics of a moving mass proposed by Misund (1993a) to account for observed variability in packing density, size and shape of herring, sprat and saithe schools.

Relatively few studies have analysed spatial pattern among schools. Soria et al. (1998) proposed a behavioural mechanism to explain the aggregation pattern of fish schools in the Adriatic and Catalan seas (Fig 1.1). They consider the spatial distribution of small pelagic fish as a dynamic patch mosaic, with several mechanisms driving space-time variations. During the aggregation phase, schools aggregate until they reach a critical size. During this process, big schools in formation result in empty space around them and corresponds to observed single (SS) and isolated schools (IS). When the school passes the critical size, dispersion starts. During the first step, big schools split into several schools of varying size, forming patches of schools (HeDS). During the second step, the patches disperse further forming a more homogeneous spatial

distribution of schools (HoDS). Depending on biotic and abiotic environmental factors, the critical size and proportion of different school sizes in each cluster may be expected to vary from one area to another.

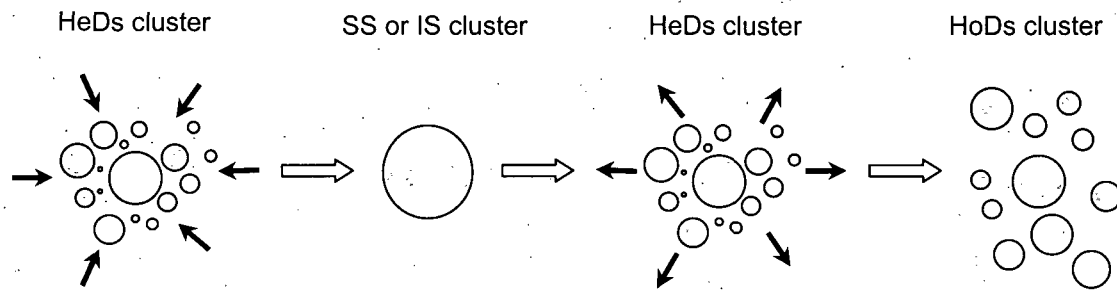


Figure 1.1 Scheme of the mechanism of aggregation explaining different types of cluster observed in Mediterranean Sea (from Soria et al. 1998). Abbreviations: HeDS – Heterogeneous distributed schools; SS – Single schools; IS – Isolated schools; HoDs – Homogeneous distributed schools.

Evolution and ecological functions of shoaling behaviour

The adaptiveness of the schooling habit is multifaceted, probably having evolved independently in many different species for a variety of reasons (Major, 1978). Included in these are selection pressures related to avoiding predation, foraging, energy conservation and reproduction. Understanding the relative importance of specific ecological functions of fish shoals has been the catalyst of many behavioural studies. A brief overview of the some functions and adaptive significance of shoaling and schooling behaviour is provided below. A thorough review can be found in Pitcher and Parrish (1993).

Predation

Many authors consider predation to be the most powerful evolutionary force since few failures in life are as unforgiving as the failure to avoid predators; being killed greatly reduces future fitness (see review by Lima and Dill, 1990). The predisposition's of individuals to acquire anti-predator skills can reflect their evolutionary history (Huntingford and Wright, 1993; Fuiman and Magurran, 1994). Minnows (*Phoxinus phoxinus*) from an English population that has lived sympatrically with pike (*Esox lucius*) for several thousand years, display much more effective and fully integrated anti-predator tactics than minnows from a Welsh population where pike were absent (Magurran and Pitcher, 1987). Furthermore, minnows from the pike exposed site are more likely to school, even in the absence of a direct attack. Equivalent differences between populations of stickleback (*Gasterosteus aculeatus*) from high and low risk areas has also been observed (Huntingford et al. 1994).

Hamilton's (1971) selfish herd hypothesis demonstrated that individual selfish avoidance of predators by cover seeking behaviour, provided a simple mechanism resulting in aggregation. Despite lowering the overall fitness of the group, the evolution of gregarious behaviour continues through the benefit accrued to individuals by their cover seeking behaviour. However, such

behaviour is typically only observed during intense predation events, individual fish apparently jostling positions.

Shoaling fish counter predator attack by avoidance, dilution, abatement, evasion, detection, mitigation, inspection, inhibition, prediction and confusion (Pitcher and Parrish, 1993) (Table 1.1). Comprehensive details of these anti-predator functions of fish shoals are provided in reviews by Godin (1986), Magurran (1990), Parrish (1992), Pitcher and Parrish (1993) and Smith (1997).

Table 1.1 Definitions of the ways in which fish shoals counter predator attacks (modified from Pitcher and Parrish, 1993, p.380).

Strategy	Definition	Example references
Avoidance	Avoiding coming into attack range of predator. Predator may or may not be detected.	Brock and Riffenburgh, 1960; Partridge, 1982.
Dilution	Reduction of risk for an individual member of a group as group size increases because predator is attacking only one of the group (or, strictly, less than the total number). Predator detected.	Foster and Treherne, 1981; Godin, 1986.
Abatement	Reduction of risk with group size for an individual member of a population because of search and dilution. Predator is detected.	Pitcher, 1986; Turner and Pitcher, 1986; Pitcher and Parrish, 1993.
Evasion	Reducing the success of an attack by moving out of strike range of a detected predator or by beating the predators manoeuvrability during a strike. May apply to individual behaviours (e.g. skittering) or to the group as a whole (e.g. flash expansion).	Hamilton, 1971; Radakov, 1973; Neil and Cullen, 1974; Milinski, 1979; Treherne and Foster, 1981; Pitcher and Wyche, 1983; Godin and Morgan, 1985; Vabø and Nøttestad, 1997
Detection	An individual becoming aware of the presence of a predator, usually (but not always) denoted by some small behavioural cue signalling alertness. Sensory cues from the predator may be direct (visual, auditory, chemosensory), or indirect, mediated via changes in neighbour fish's behaviour signalling alertness.	Magurran et al. 1985; Godin et al. 1988.
Mitigation	Reducing the probability of success of an attack which has already been launched by a detected predator.	Neil and Cullen, 1974; Pitcher and Wyche, 1983.
Inspection	Gaining information about a potential predator while approaching it and then returning to the group.	Pitcher et al. 1986b; Milinski, 1987; Magurran and Higham, 1988; Pitcher, 1992; Magurran, 1990.
Inhibition	Reducing the likelihood of a detected and attacking predator launching a strike.	Breder, 1959; Hobson 1968; Pitcher 1979; Pitcher, 1992.
Confusion	Reducing the success of an attack that has been launched, by beating the predator's sensory or cognitive capacity.	Nursall, 1973; Ohguchi, 1981; Landeau and Terborgh, 1986; Pitcher and Wyche, 1983; Magurran and Pitcher, 1987.

Foraging

Foraging in shoals confers several adaptive advantages to individuals. Keenleyside (1955) and Morgan (1988) found that shoals can benefit members by enhancing the chances of finding food. Shoaling can increase the volume searched and thus probability of finding food in one of two ways; either by swimming in large shoals or swimming in smaller shoals, but reducing the packing density to increase the area. Shoal members may benefit from passive (Pitcher et al. 1982) or active information transfer (Magurran, 1984) relating to feeding opportunities. Moreover, reduced handling time of food items in shoals (Street et al. 1984), provides individuals with more time to watch for predators (Magurran et al. 1985).

Reproduction

The benefits of social aggregation during a spawning season hardly need explaining. Even many non-schooling fish exhibit social behaviour in the form of shoaling during spawning season. For batch spawning species such as herring who typically have a single, discrete, rather short spawning period (Hay, 1985) it is essential individuals congregate in spawning areas at the same time. Shoaling and homing behaviours maintain the social contact necessary to achieve such coordination and thus can be considered adaptive precisely for the purpose of reproduction.

Energy conservation

Energy saving conferred by hydrodynamic advantage has frequently been proposed as selection for schooling behaviour. Herskin and Steffenson (1998) provide evidence in support the early work of Weihs (1973, 1975), who predicted that schooling fish enjoyed a potential 40% reduction in energy expenditure. In their experiment, individual seabass (*Dicentrarchus labrax*) swimming at the back end of school had a significantly reduced tailbeat frequency that translated to 9-23% reduction in the oxygen consumption rate. Breder (1976) postulated that individuals benefit from vortex trails left by fish in front and decreased drag resulting from the lubricity of mucus-water mixture within a school. Despite empirical evidence for a lateral push-off effect (Partridge et al. 1983; Pitcher et al. 1985), Pitcher and Parrish (1993) have argued against hydrodynamic advantage as a major selective force in fish schools.

Learning

Learning by social transmission, from other, usually older, individuals permits the rapid acquisition of behavioural traits that may enhance survival, and thus, is intimately related to the ecological function and evolution of social behaviour. Magurran and Higham (1988) demonstrate that shoals of minnows switch their behaviour after observing the response of threatened fish, confirming information about an approaching predator is transferred across the shoal. Information between the transmitter and receiver fish may be transferred passively (as in head down foraging of minnows) or an element of manipulation may be involved. Soria et al. (1993) showed that even "primitive" clupeids such as the thread herring (*Opisthonema oglinum*) can learn; stress conditioned fish were found to lead school reactions when mixed with non-conditioned (naïve) fish. Similar learning opportunities may exist in nature where school fidelity is low (Helfman, 1984). Experiments on social traditions of French grunts provides evidence that

social learning of migration routes is modifiable, and that such flexibility is adaptive when directions of migrations are influenced by selection pressures such as predator distribution and activity (Helfman and Schultz, 1984). In general, younger fish have been observed to follow older fish during migrations (Harden-Jones, 1968; Hourston, 1982; Rose, 1993). The older fish presumably follow known landmarks experienced and learned in previous years (Baker, 1978). In herring, there is evidence that migration is controlled by both genetic factors and through learning processes (Corten, 1993). Shoaling could also increase the accuracy of homing on migration, since the mean direction or route is likely to be a more accurate estimate of the correct destination than any individual's choice (Larkin and Walton, 1969).

*Allowing
co-existence*

Schooling has also been proposed as a mechanism whose adaptive function lies in circumventing the territoriality of competitors (Robertson et al. 1976). Experiments showed that non-territorial striped parrot fish (*Sacarus croicensis*) that schooled enjoyed higher feeding rates and were attacked less often by territory owning competitors (damselfish, *Eupomacentrus planifrons*), than their non-schooling counterparts. In this example, schooling behaviour functioned to promote the co-existence of two competing species.

*Behavioural
plasticity*

It is clear from the above discussion that several important functions performed by the shoaling/schooling habit may have adaptive significance, although the risk of being preyed upon (in ecological time) is probably the most powerful selecting force, since death denies any future. It is important to note however, that risk of predation does not constrain behaviour, rather it is an integral part of a wide variety of decision making processes (Lima and Dill, 1990). Individuals make frequent decisions evaluating the costs and benefits of shoaling, trading off conflicting motivational pressures of hunger, avoiding predation and reproduction. It is the trade-offs resulting from decisions on whether to join, leave or stay with a shoal (JLS rules; Pitcher and Parrish, 1993), that produce instability within shoals.

Their phenotypic plasticity (West-Eberhard, 1989) allows individuals to develop appropriate behavioural repertoires for the environment they find themselves in (Fuiman and Magurran, 1994) and consequently produces the observed dynamic changes in shoal structure and distribution. In the words of Radakov (1973), "The character of the shoal is that of a labile adaptation to changeable conditions".

1.2 Instability of Herring Fisheries

Vulnerability

Fisheries which exploit herring and other small schooling pelagic fish are intrinsically unstable since they target the species in such a way as to weaken the very features that they have evolved for persistence in a variable environment. Beverton et al. (1984) classified fisheries on small schooling pelagics as high risk, being considered exceptionally unreliable and vulnerable to unrestrained fishing. The numerous examples of stock collapse more than justify this

classification. Although many elements ultimately contribute to the vulnerability of herring fisheries to overexploitation one of the most profound is the interaction of the behaviour of fish and fishers.

Catchability

The technology and techniques employed in modern fishing fleets ensures they are extremely efficient at detection and capture of fish schools. Compounding this effect, two natural behavioural responses have been observed in herring (and other schooling fish) that makes them remain almost equally vulnerable to capture, even during declining abundance. First, as the stock declines, average school size may be maintained, and secondly, the overall area occupied by the stock may decline (Winters and Wheeler, 1985; 'range collapse', Pitcher, 1995). Thus, average density of schools remains the same with the consequence that fishers may achieve an almost constant catch per unit effort (CPUE), regardless of stock abundance. Expressed in terms of catchability, the relationship is such that catchability increases as stock abundance declines. Density dependent catchability of this form has been observed for the California sardine (MacCall, 1976), Peruvian anchovy (Csirke, 1989), Norwegian spring spawning herring (Ulltang, 1976), South African sardine (Shelton & Armstrong, 1983) and Atlantic menhaden (Schaaf, 1980).

Incorporating density dependent catchability into a simple surplus production model, Pitcher (1995), developed three models (Figure 1.2) to explore the consequences of schooling behaviour and high technology on a hypothetical stock. Even when stocks are at low abundance, density dependent catchability lead to rapid decline to the point of collapse, hence the problem was termed catchability-led-stock-collapse (CALSC) (Pitcher, 1995).

Economics

Incorporating economic behaviour, Mackinson et al. (1997a) extended the models to investigate the dual impacts of fish and fishers behaviour on the fishery. Including some basic economic features relating to cost of harvesting, price of catch and investment incentives can accelerate the rate of stock depletion predicted by the constant CPUE and Csirke-MacCall models (Figure 1.3). When fishers fail to co-operate or are subsidised, the constant CPUE model predicts that profits accrue so quickly to fishers that they continue to invest in fishing even when a stock collapse is imminent. In this situation the increasing catchability is the primary driving force governing the dynamics of the model, and the phenomenon of CALSC (Pitcher, 1995) is clearly seen. Similarly, the dynamics of density dependent catchability in the Csirke-MacCall model results in the stock being driven to collapse, even when fishers try to dis-invest. An obvious yet important conclusion from the analysis is that the Schaefer model, typically used by fisheries economists, cannot capture some of the important behavioural processes that are apparent in fisheries for small schooling pelagic fish, and is therefore inappropriate as a basis for the management of such stocks.

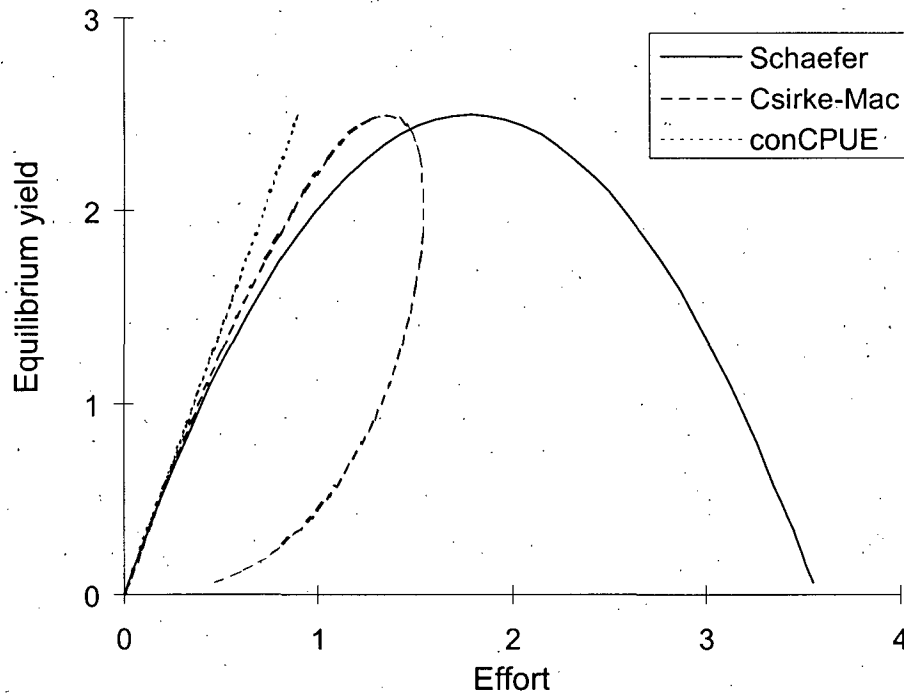


Figure 1.2 Sustainable yield upon fishing effort curves for the three models*; Schaefer, Csirke-MacCall, Constant CPUE. For all three models parameters are $B_{\infty} = 100$, $q = 0.028$, k (rate of biomass increase) = 0.1, and for Csirke-MacCall: $a = 0.177$, $b = 0.4$.

**The Schaefer Model* - constant catchability. Where CPUE (U) declines as effort (E) increases and tracks the decline in population biomass as the population is depleted, $U = Y/E = qB$. The essential feature is that catchability (q) is a constant: $q = U/B$. The exact form of the equation is not important since essentially the same results derive from the various modifications to this model. The sustainable (=equilibrium) yield is a parabola on fishing effort.

The Csirke-MacCall Model - for schooling species where a whole schools can be caught almost irrespective of total stock density, catchability increases in inverse proportion to stock abundance. The relationship is: $q' = aB^{-b}$, where a is a proportionality constant and b is the degree to which catchability increases as stock declines. In the Csirke-MacCall model, substituting q' for q in the Standard Schaefer model results in backward bending production curve.

The constant CPUE Model - if CPUE actually remains constant (a result of modern fishing technology) with declining stock size an even more drastic model is produced. Here, since $Y/E = U$ is constant, q' increases: $q' = B_{\infty} q/B$. When q' is substituted for q in the standard Schaefer model, yield increases in direct proportion to effort up to a maximum value and then decreases along the same line.

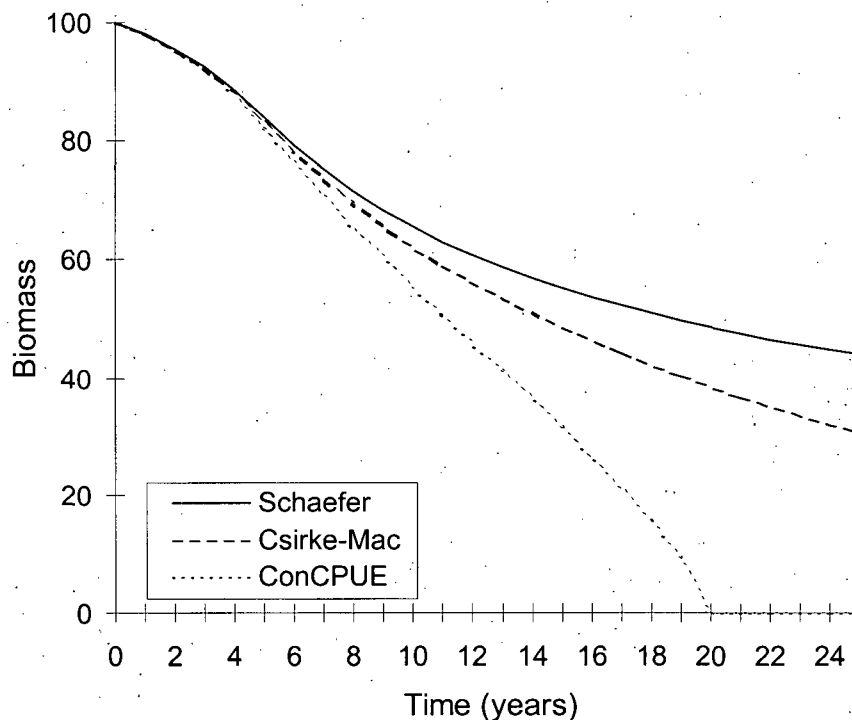


Figure 1.3 Biomass changes predicted by three bioeconomic models during non-cooperative behaviour of fishers (from Mackinson et al. 1997a).

1.3 Ecological importance

Ecosystem consequences

Over the last fifty years a dramatic catalogue of stock collapses have involved small pelagic forage fish. Beverton (1990) provided a review of small pelagic stocks using five criteria to consider whether they are at threat of over harvesting. Despite herring being exceptionally susceptible to the pressure of overfishing they were considered to have good persistence in an ecological sense. Some of the largest herring populations are known to have waxed and waned over the centuries (e.g. Norwegian spring-spawning herring, see Dragesund et al. 1980). Although loss of genetic variability was considered a valid threat, evidence from Stephenson and Kornfield (1990) showed Georges Bank herring recovered unchanged with distinct genetic constitution from neighbouring Nova Scotia Banks population. Beverton (1990) concluded that the likelihood of harvesting small pelagic species to extinction was remote, but warned against more subtle consequences to the ecosystem that may result from collapse of a major population. He suggested that there was "some inferential (and disturbing) evidence that the disappearance of some 10 million tonnes of biomass and loss of recruitment in the form of adult Norwegian spring spawning herring and 2 million tonnes from the North Sea may have resulted in re-orientation of the flow of production into alternative stable states". Some believe this re-orientation of flow was responsible for the "gadoid outburst" (Cushing, 1980) in which there was a significant increase in the production of gadoid species corresponding with the decline of

herring stocks. In a review of cases of replacement, Daan (1980) concluded that for the North Sea some sort of replacement was 'likely'.

Structure & stability

Structure and stability of ecosystems has been widely discussed in the ecological literature (see for example Elton, 1958; MacArthur, 1955; May, 1981, 1983; DeAngelis, 1975; Pimm, 1979), but despite some pioneering analyses (Beddington and May, 1977) there have been few rigorous attempts to model and predict the potentially devastating long term ecosystem consequences of over-fishing. Contrary to the reality that fisheries are generally not restricted to catching one species alone, the development of single species models for fishery management have centred around that very assumption. Due to our lack of ability to model complex systems, such methodology is still prevalent. The multispecies assessment approach (e.g. Mercer, 1982) takes for granted the idea that what is taken from one stock may be lost or compensated for by another. However, mainly due to the large number of parameters required to be estimated, multispecies models have generally been difficult to implement and the growing concern that it is necessary to consider interactions within an ecosystem has remained largely unmet. Management based on an 'ecosystem principle' demands that we have a crystal ball to ask 'what if?' questions (Larkin, 1996).

Resistance & resilience

Mackinson et al. (1997b) used a new dynamic mass-balance model, ECOSIM (Walters et al. 1997) to compare the ecosystem impacts of four contrasting fishing regimes on small pelagic fish in 3 upwelling ecosystems. The observed dynamics demonstrated that small pelagics play a central role in the three up-welling ecosystems studied. Their direct link to phytoplankton and zooplankton food resources has significant implications for system productivity, a point emphasised by the declines of commercially important competitive species when the biomass of small pelagics increased. Measurable attributes that further demonstrate the importance of small pelagics in ecosystems are; (i) their high throughput of energy; (ii) their intermediate trophic level; and (iii) high connectivity to other components to in the ecosystem.

Within the upwelling systems studied, small pelagics displayed poor resistance to disturbance, biomass changes occurring rapidly at the onset or release of fishing pressure. However, the short recovery time relative to higher trophic levels, indicated a greater degree of resilience, a feature that is likely a consequence of their high throughput. Within the systems small pelagics were considered dynamically fragile (responding rapidly to perturbations) but globally robust (recovering to previous or new equilibrium, Begon et al. 1990). Their high connectivity to other groups dictates that changes in biomass of small pelagics ought to have important consequences to the stability of an ecosystem.

Depleting stocks of small pelagics through fishing will have important consequences for fisheries on other commercially important species. Where these other species are dominant predators of the small pelagics the likely outcome is a reduction in their biomass and catch. The converse

may be true when the target species is a competitor, the increased biomass of food sustaining greater biomass of the competitor. The economic importance of herring and other small pelagics, together with their central role in the ecosystem, are two demanding reasons why it is imperative that we understand how these changes are brought about and assess the likely consequences to other commercially important fish and other species within the ecosystem. The recent evidence for fishing down the marine food web (Pauly et al. 1998) further highlights this need.

Pitcher et al. (1998) used a multidisciplinary approach to assess the 'health' or sustainability of herring fisheries. Fisheries were ordinated according to ecological, economic, biological and social sustainability. Historical trends for the North Sea, British Columbia and Norway were also assessed. In general, Pacific herring fisheries ordinate in 'better' positions than Atlantic herring fisheries; West Atlantic better than East Atlantic, Alaskan better than British Columbia for Pacific herring, sardines and anchovies better than herring fisheries.

1.4 Thesis outline

Rationale and objectives

Although there is considerable insight in to why herring shoal, the precise factors that determine changes in structure, dynamics and distribution are not well understood. The effect of particular internal and external factors changes markedly across spatial and temporal scales and this problem alone severely hampers the ability for studies to tease out and conclusively demonstrate the relative roles of each factor.

For the most part, previous studies have been directed to small scale (0.1 to 10 m, seconds to minutes), school organisation and dynamics (experimental tank behavioural studies, see Pitcher and Parrish, 1993 for review); or, large scale (100's km, weeks to months), stock structure and migration studies (e.g. Harden-Jones, 1968; McKeown, 1984). Information on the meso-scale (0.1 to 100 km, hours to weeks) distribution pattern of schools and school clusters is particularly lacking. It is at this spatial and temporal resolution that studies are required to develop spatially explicit predictive models needed for management and to allow us to respond to change. To do so, we must learn how to interface disparate scales of interest, bridge 'gaps' in our scientific knowledge, and learn to understand how information is transferred from fine to broad scale and vice versa (Levin, 1992).

Since many herring fisheries are typically conducted at spatial scales of one to tens of kilometres and occur for periods of days to weeks, both fishers and fishery managers alike operate within the same meso-scale realm as the fish. By virtue of their profession, it is prerequisite that they have knowledge regarding the distribution and behaviour of herring. Such rich information can be used to bridge gaps in our current scientific knowledge. Unfortunately, the attitude of many

biological scientists and natural resource managers to local knowledge has been dismissive (Johannes, 1989). Typically, the labelling of local ecological knowledge by more conventional analytical fisheries science as 'anecdotal', has resulted in its absence from stock assessment and management. William Broderick, a commercial fisherman observes that recently "It has become politically correct to invoke fishermen as part of the [information-gathering] process ... but there is very little will actually to do it" (Strauss, 1997).

The objective of this research is to demonstrate a method by which knowledge of the behavioural ecology of herring can be used to predict changes in structure, dynamics and meso-scale distribution of shoals. Furthermore, to consider implications of spatial and temporal changes in shoal structure and spatial distribution pattern for the management of herring fisheries. Two themes are encompassed within the methods:

- the thesis that spatial and temporal changes in factors influencing the behaviour of individual herring are manifest as predictable modifications of shoal structure, dynamics and distribution.
- the importance of incorporating multiple sources of information (in particular, local knowledge) to maximise problem solving capabilities.

Using a fuzzy logic expert system (see below) my research develops a formal framework for combining local ecological knowledge and scientific knowledge in the form of heuristic rules. It demonstrates how to predict the structure and distribution of shoals for 2 species of migratory adult herring during different phases of their annual life cycle. The model is called "CLUPEX". (The name CLUPEX is derived from *Clupea* (scientific name for herring) and 'Expert system').

Some potential users of CLUPEX include: researchers interested in generating testable hypotheses on spatial dynamics of schooling fish; fishery managers using CLUPEX as a training resource tool and for guidance during in-season management (particularly where CLUPEX predictions are adapted to specific local conditions); students and teachers of fish behaviour as an educational tool; those interested in learning more about fuzzy reasoning and developing practical applications based on qualitative knowledge.

Three sources of information contribute to the rule-base of CLUPEX: field research surveys, scientific literature and interviews with fishers, First Nations, scientists and fishery managers. Detailed information from all sources is stored separately in the "Knowledge-base", a Microsoft Access (97) database.

Methods - Expert Systems and Fuzzy Logic

Expert systems are a branch of artificial intelligence; theories and methods for automating intelligent behaviour. They are computer programs that provide assistance in solving complex problems normally handled by experts. They use rules to store knowledge. When the system is asked to solve a problem, it uses this knowledge to infer solutions. Typically, they are used to solve problems that cannot be solved by a purely algorithmic approach, those that have an

irregular structure, contain incomplete or uncertain knowledge, are considerably complex and where sometimes, 'best guess' solutions must be obtained by reasoning from available evidence. They differ from conventional computer programs in four respects (Dabrowski and Fong, 1991):

- I. Knowledge is separated from program control;
- II. Knowledge is represented declaratively (declarative knowledge states what exists, not how it is applied);
- III. They perform computation through symbolic reasoning (symbolic information is information that does not contain numeric values. Symbolic reasoning is intended to emulate the way that humans manipulate concepts and ideas);
- IV. They can explain their actions.
- V. They can make mistakes as experts do.

How an expert system works is shown schematically in Figure 1.4.

Expert systems can be developed using software building tools. The developer is provided with a shell that consists of the inference engine, a mechanism for inputting and editing rules, an explanation facility and necessary tools to design specific interfaces for the end user.

Prior to PC-based building tools becoming readily available, expert systems were notoriously time consuming to develop. For example, a modest system of 200 rules, "PUFF", used to analyse pulmonary functions, took 7 people 2 years to develop; many projects were never realised. Of the successful systems, many have been developed for diagnostic features such as in medicine (e.g. MYCIN) and for machine technical faults (Dabrowski and Fong, 1991). Warwick et al. (1993) identify 98 references to expert systems in the field of environmental management. In a review of fishery-related expert systems, Saila (1996) offers a list of only 18 judged to be relevant. Of these, only 2, Aoki et al. (1989) and Fuchs (1991), both non-fuzzy systems, address linkages between fish and environment.

Fuzzy logic (Zadeh, 1965) can also be incorporated within expert systems. In fact, its implementation has lifted the development of expert systems out of a stagnant phase. Heuristics are the basis of fuzzy logic and the formal framework for their use in expert systems has yielded proficient and more easily developed systems. Linguistic terms used to define fuzzy sets provide the ability to capture the uncertainties and vagueness embedded in heuristic statements. Use of fuzzy expert systems in ecological modelling is a new field. There have been relatively few applications spanning a variety of disciplines. A good overview can be found in a special issue of Ecological Modelling (#85, 1996) that publishes a collection of papers from a 1993 workshop on Fuzzy Logic in Ecological Modelling held in Kiel, Germany.

Fuzzy logic is not a logic that is fuzzy but a logic that describes and tames fuzziness. It is a theory of sets, sets that calibrate vagueness (McNeill and Freiburger, 1993). It has a rigorous mathematical foundation that has been shown to encompass probability theory (Kosko, 1990), rather than contradict it. The essence of fuzzy logic rests on the truism that all things admit degrees of vagueness. Black and white cases are the exception in a world of grey. For example,

the distinction between someone who is *medium* in height and someone who is *tall*, is vague (Figure 1.5). The categories overlap and may also shift in different contexts. In Figure 1.5, the terms in italics are fuzzy terms. In set theory, each of these linguistic values is a set or member of the fuzzy variable height. There is no one point where we can say someone is tall or not-tall. It is a matter of degree. Fuzzy sets deal with the vagueness that is rife in language, and ironically they are more precise than traditional two valued or even multi-valued logic since they are able to show the continuum. "Because fuzzy sets model words mathematically, they map the numerical on to the verbal and can bring these two worlds in to sync" (McNeill and Freiburger, 1993).

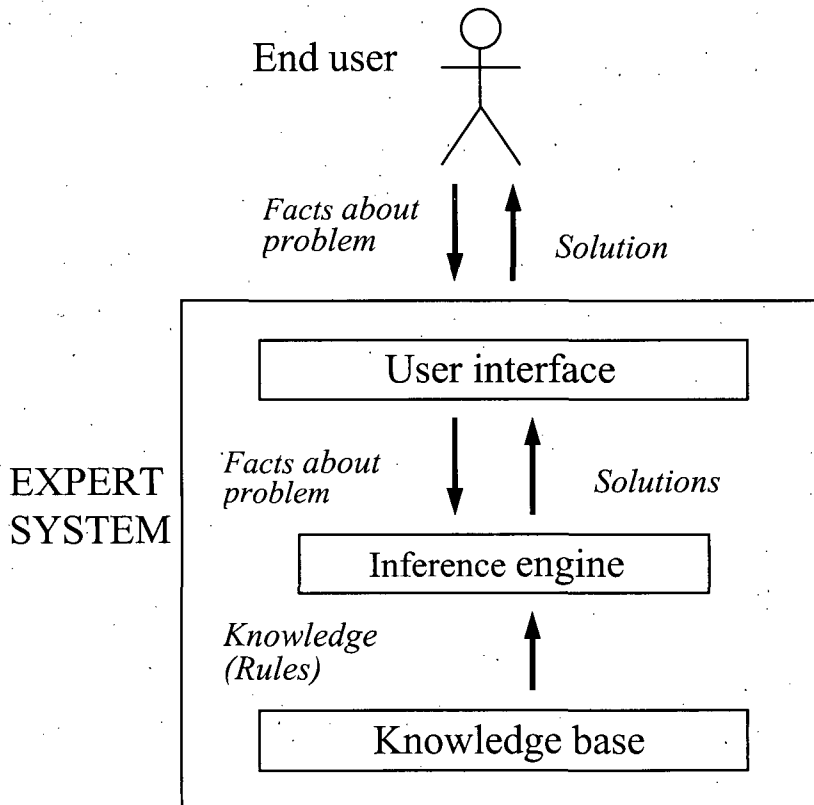


Figure 1.4 Schematic of an Expert System (redrawn from Dabrowski and Fong, 1991).

Knowledge Base – knowledge is stored as RULES, either in the form of heuristics (rules of thumb) and/or as and more complex mathematical algorithms. Most rules have the format “**IF** a certain situation occurs **THEN** a known outcome is likely” and several may be combined with AND statements. The level of certainty in the outcome can be defined explicitly. ‘Rules’ are gathered from expert sources, manipulated and input to the knowledge base by the “knowledge engineer”.

Inference Engine - the inference engine determines how rules will be used to infer conclusions. The engine uses predetermined rules to define different inference strategies. There are two inference strategies:

- i) Backward chaining - picks a solution and reasons backward testing rules to infer facts that may substantiate the solution. This strategy is said to be “goal driven” and is normally used when there are a small number of solutions and a large number of initial facts. This is essentially a selection process.
- ii) Forward chaining - used when there is a manageable number of initial conditions and a large number of potential outcomes. Forward reasoning is “data driven”. Given the conditions it searches forward for possible solutions and therefore may be seen as a predictive process.

The inference engine compares rules against known facts (input by user), stored in a **context file**, to determine if new facts can be inferred. Solutions are returned to the context file.

User Interface - provides the link from system to user. In its simplest form it may be text. More specifically it may be designed using graphics and hypertext. An important element is the facility to provide explanation of the actions of the system. At any time the end user should be able to ask, why?

The rules in a fuzzy expert system are usually of the form similar to the following:

IF X is *High* AND Y is *Low*

THEN Z = *Medium*

Where X and Y are input variables (names for a known value), Z is an output variable (a name for a data value to be computed), *High* and *Low* are membership functions (fuzzy subset) defined on X and Y respectively and *Medium* is a membership function defined on Z. The antecedent (the rule's premise) describes to what degree the rule applies, while the conclusion (the rule's consequent) assigns a membership function to each of one or more output variables (Kantrowitz et al. 1997).

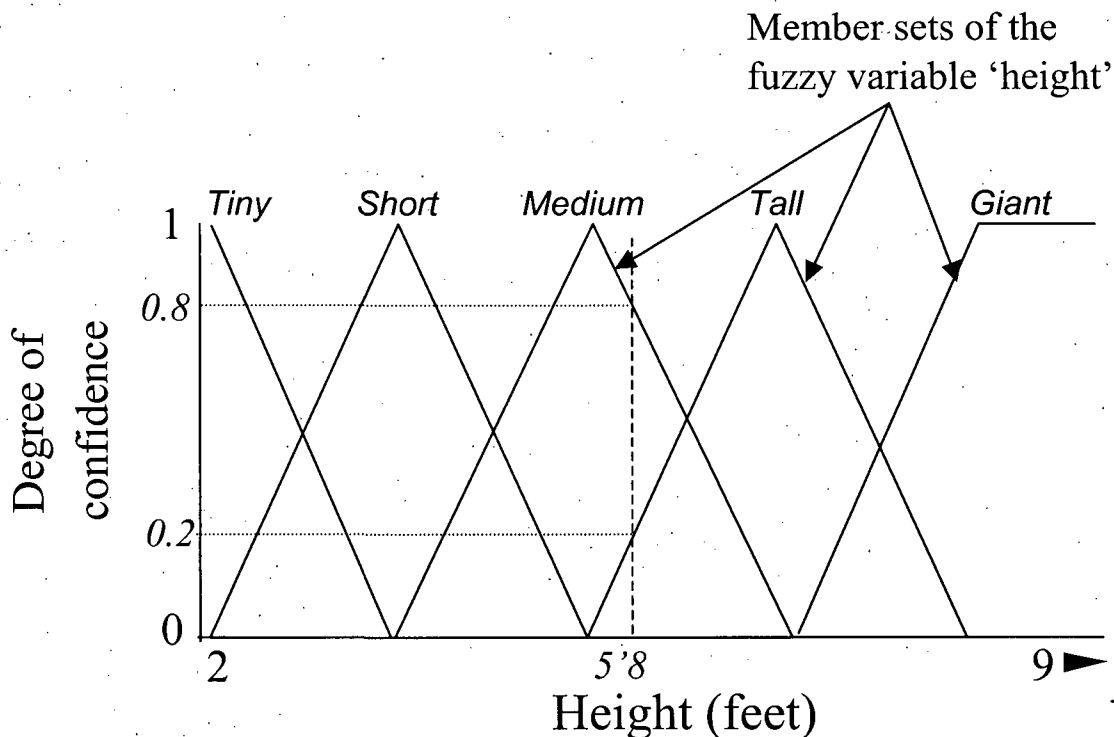


Figure 1.5 Fuzzy sets on the fuzzy variable 'height'. The sets (also sometimes called members or subsets) are the linguistic concepts; *tiny*, *short*, *medium*, *tall* and *giant*. The triangles are the memberships functions of each set. The slope and degree of overlapping of the membership functions is the key element determining how unique or fuzzy each set is. The degree of confidence on the Y-axis shows our degree of belief in the linguistic concepts. For example, when Caroline's height is 5'8 we are 0.8 confident that she is of *medium* height and also 0.2 confident that she is *tall*. In an expert system both pieces of information are used simultaneously to make conclusions, thus avoiding the simplistic notion that something is or is not true, when in fact it may be both to different degrees.

Structure

Chapter 2 details quantitative, descriptive data on structure, dynamics and distribution of herring shoals from 3 research cruises. Two surveys on pre-spawning Pacific herring are combined in an examination of pattern and variability in structure and distribution herring shoals between regions; the Strait of Georgia (1997) and Central Coast (1998) (note that the Central Coast survey data is not incorporated in the knowledge-base but is used as 'new' data to test model predictions - see Chapter 5). The third survey was conducted in the Norwegian sea during May 1998 in collaboration with Norwegian colleagues from the Institute of Marine Research and University of Bergen. It addresses specific issues of scale in an examination of ocean feeding Norwegian spring spawning herring. The surveys yield quantitative descriptive data on herring shoals during different biological and environmental conditions.

An overview of literature concerning field and experimental studies on behaviour, structure, dynamics and distribution of herring and other schooling pelagic fish is provided in Chapter 3. The studies provide the foundation for many of the behavioural rules in addition to quantitative information on herring shoals.

Chapter 4 discusses information from 31 interviews with fishers, fishery managers, scientists and First Nations people. Comparisons are made between the knowledge from different interview sources and with that obtained from literature. The knowledge from interviews is primarily qualitative and descriptive in nature and used to define rules linking biological and environmental factors to changes in herring shoal structure, dynamics and distribution.

The qualitative and quantitative information documented in chapters 2, 3 and 4 is stored with the Knowledge-base, a Microsoft Access 97 database (file: knowledge.mde). Examination of this file while reading these chapters is encouraged. For full instructions on how to open and view various parts of the Knowledge-base, see file "Readme.html" or Readme.doc" on the enclosed CD-rom.

All aspects of the CLUPEX model development strategy, operation, results and sensitivity analysis/ robustness are documented in Chapter 5. In the results section of Chapter 5, two full examples of the model in operation are provided, demonstrating the inferencing process in which the system queries the rule-base to make predictions. Model predictions of the two example runs are compared to published field observations and predictions based on theoretical and experimental work. Additional predictions are also made and discussed in the text. Examination of the model (enclosed on CD-Rom) is encouraged while reading the sections on operation and results. The hypertext file, called "Readme.html" or "Readme.doc" describes how to operate CLUPEX and its explanation facility so that readers may see how the model derives its conclusions.

Chapter 6 considers potential applications and implications of the model. In section 6.2, the development of a Visual Basic graphic output model (ShoalPattern) that interfaces with CLUPEX in the generation of meso-scale shoaling patterns is detailed. The conceptual elements and initial equations, formulated with the aid of N. Newlands, are reported in Chapter 6. Further details and future advances of the model will be elaborated on in a future publication (Newlands and Mackinson, 1999, in prep) and in the thesis of N. Newlands. In section 6.3 a conceptual model of a herring fishery is developed to explain how output from the CLUPEX and ShoalPattern models can be applied in an examination of spatio-temporal fishing tactics in herring fisheries. It is intended that the theoretical consideration outlined here will provide a starting point for future work.

The summary and concluding comments in Chapter 7 discusses benefits and limitations of the expert system approach, comparing it with alternative methods. I expand on how the approach can be used in other areas of resource management, giving suggestions for future work using local knowledge that applies the principles of expert systems and fuzzy logic.

Chapter 2

Herring Shoals in the Wild

My field research surveys on structure, dynamics and distribution of herring shoals is described in two sections. The first addresses specific issues of scale in an examination of ocean feeding Norwegian spring spawning herring. The second combines two surveys on pre-spawning Pacific herring in an analysis of pattern and variability in structure and distribution of herring shoals between regions (note that the Central Coast survey data is not incorporated in the knowledge-base but is used as 'new' data to test model predictions - see Chapter 5).

In addition to contributing considerable quantitative data necessary to describe and predict spatial organisation of herring shoals, the surveys yield supporting information on the behavioural responses of herring to different biotic and abiotic conditions; this knowledge is used in the development of rules describing the relationship between herring and their environment.

Data considerations and statistical methods

A potential problem that is not addressed fully in the data analyses concerns the spatial correlation between schools that are close in space, and particularly those that are adjacent. Where neighbouring schools are more alike than those further apart, the data are said to be spatially autocorrelated and each school does not provide an independent observation (Haining 1993). In effect, the data set will be equivalent to independent data at a smaller scale of measurement. The effect of autocorrelation will appear mainly in the tests for significance using classical statistical methods, with a tendency for the relationships to be more significant than they really are (Legendre 1993, Nash et al 1999).

Spatial autocorrelation is a recognised and accepted feature of the studies presented here, and whilst specific statistics for measuring and assessing it (Odland 1988) have not been employed, it has been an explicit goal to attempt to identify factors resulting in similarities between schools found close together. Furthermore, even if echosounders and sonars permitted measurement at a smaller scale (although undesirable for the present study), spatial autocorrelation is still likely to exist, and thus the problem would remain unresolved. For this reason, school observations are treated as independent and classical statistical analyses are performed.

The students *t*-test was used to test the difference in sample means of various school descriptors. In addition to the samples being normally distributed, an assumption of the *t*-test is that both samples are believed to be independent estimates drawn from the same population. This assumption was tested by using an *F*-test to compare the ratio of the variance from the two

samples. For instances where an F -test indicated that the sample means were not drawn from the same population, a modified t -test procedure, with reduced degrees of freedom, was applied. Using the null hypothesis that the mean of the samples were equal ($H_0: \mu_1 = \mu_2$), the significance of t -tests was evaluated at the 95% confidence level by comparing the computed test statistic to a critical value from a t -distribution based on 'two-tails' of the probability distribution. Where observations indicated prior reason to suspect that one sample mean was greater than the other ($H_0: \mu_1 > \mu_2$), significance was evaluated based on one-tail tests.

For discrete or ranked data, tests of significance between sample means were performed using a non-parametric procedure, the Mann-Whitney U -test. Regression analyses were performed to examine the relationships between variables.

2.1 Cross-scale observations on structure, distribution and behavioural dynamics of ocean feeding Norwegian spring spawning herring.¹

INTRODUCTION

Description of pattern is synonymous with description of variation. Accordingly, concepts of scale and pattern are inevitably fused since determination of scales is a prerequisite to understanding variation (Denman and Powell, 1984). Lack of explicit consideration of spatial and temporal variation often occurs because simple patterns are more easily observed from 'homogenisation' of the data spatially or temporally. Yet, since each species observes the environment on its own unique suite of scales of space and time (Weins, 1976), variability is not an absolute and only has meaning relative to a particular scale of observation (Levin, 1992). Moreover, since variation in local density of marine organisms reaches high values at some spatial scales and low at others, parameters characterising local density dependence may only apply at certain spatial scales (Schneider, 1989). Consequently, particular ecological processes may be better studied by explicit simultaneous consideration of spatial and temporal components (Resh and Rosenberg, 1989).

Processes that result in the observed distribution pattern and structure of herring schools can be viewed as being derived from a hierarchical complex of space-time events. At the lowest spatial level (micro-scale, cm to m), individual fish execute second to second trade-offs, evaluating the profitability of joining, leaving or staying with other fish (Pitcher and Parrish, 1993). Such decisions generate the internal dynamics of herring schools, which are characterised by changes

¹ Parts of the work contained in this section have been the basis of a publication, Mackinson et al. (1999b)

in internal (packing density) and external (shape) structure (Pitcher and Partridge, 1979; Misund et al. 1995). At the next level (small meso-scale, 10's m to 100's m), we observe school movements and interaction among schools such as joining and splitting. These actions can also be extremely dynamic, occurring within a short time scale (minutes) and often in response to specific events (Pitcher et al. 1996). The large natural variability of school size testifies to this dynamic situation (Misund, 1993). It is at the small meso-scale that many of the interactions between predators and pelagic prey take place (Schneider and Piatt, 1986; Vabø and Nøttestad, 1997). The next two higher levels (large meso-scale, 100's m to 10's km; and macro-scale, 10's to 100's km) focus our observations on distribution patterns between schools or school clusters and the range occupied by a stock, with the associated temporal scale of interest spanning days to weeks, and months to years, respectively. Large meso and macro-scale distribution may vary in a characteristic manner during different life history phases (Fernö et al. 1998), and has been shown to be directly linked to spatial and temporal distribution patterns of oceanographic features and conditions (Reid et al. 1993; Maravelias et al. 1996). To gain insight to the basic mechanisms and processes that govern the repertoire of herring behaviour, and how this relates to distribution pattern of schools, requires that our studies traverse spatial and temporal scales.

During April, Norwegian spring spawning herring migrate in schools (*sensu* Pitcher, 1983) from the coast north-westwards to the region of a cold front, a rich feeding ground which they follow north and eastwards throughout the summer (Røttingen, 1992; Dragesund et al. 1997). Motivation to feed is considered to be the primary driving force governing the migration although intense predation at the Norwegian coast may also be important (Fernö et al. 1998). Previous surveys of the *Mare Cognitum* program (see IMR, 1997) have revealed that during the ocean feeding period the macro-scale distribution of herring is closely linked to that of food (Melle et al. 1994), but may potentially be modified by competitive interaction with other pelagic planktivores such as blue whiting, and also by predation pressure from a variety of species including saithe, cod, haddock, fin whales, false killer whales, white sided dolphins, killer whales (Christensen et al. 1992; Haug et al. 1995; Similä et al. 1996; IMR 1997), and sea birds (Anker-Nilsson and Barret, 1991; IMR, 1997; Fernö et al. 1998).

Although fish in larger shoals may gain benefits through sampling behaviour (Pitcher and Magurran, 1983), for hungry fish it is suggested that smaller, less cohesive schools are better for optimal foraging, a reduced overlap of perceptive field resulting in less competition and less interference of individual feeding acts (Blaxter, 1985). Laboratory and field observations have revealed that feeding fish have a tendency to spread out and schools are often horizontally flattened in shape (Nøttestad et al. 1996). They choose to be in smaller schools, are less cohesive (Morgan, 1988), have a reduced packing density and display increased behavioural activity (Robinson, 1995). In the absence of predators, shoaling fish congregate according to the

profitability of food patches (Milinski, 1979; Godin and Keenlyside, 1984) or where food patches are found (Robinson et al. 1995). Diurnal vertical migrations may track that of prey species.

Experiments demonstrate clearly that prey animals measure risk when deciding whether to forage (Morgan and Colgan, 1987; Lima and Dill, 1990; Milinski, 1993). In herring, the shoaling rules (and consequently shoal structure and distribution) are modified when fish are forced to make trade-offs between foraging and avoiding predation. Since risk of predation has evolutionary priority over feeding (Life-dinner principle, Dawkins and Krebs, 1979), in the face of potential predation, individuals will behave according to perceived risk. For example, when fish are well fed and food is abundant, reduced competition and the desire to maintain anti-predator advantages of larger shoals may result in the joining of shoals.

Although a considerable knowledge of changes in structural characteristics of schools has amassed, there is very limited understanding of meso-scale distribution characteristics; changes in the pattern within and between school clusters. The analysis of the herring schools in the Norwegian Sea has two objectives; (i) to characterise the large meso-scale spatial distribution and changes in diurnal distribution of schools using a descriptive index (Cluster Ratio) that compares clustering patterns of schools between locations and seasons; (ii) to link large and small meso-scale observations based on the pre-supposition that the structure, dynamics and distribution is a consequence of evolutionary adaptive behaviour associated with feeding and avoiding being eaten. Based on previous lab and field studies on schooling fish, we specifically hypothesise that during this period of ocean feeding that on average, school size will be small, packing density low and vertical and horizontal distribution of schools will be related to feeding activity. Moreover, school dynamics ought to reflect a dynamic regime of adjustments according to tradeoffs associated with feeding and predation risk.

MATERIALS AND METHODS

Biological, physical and acoustical data were recorded from a scientific cruise in the Norwegian Sea during 6th – 22nd April 1997, on board the research vessel “G.O.Sars”. The survey consisted of one diagonal and four parallel transects spaced thirty nautical miles apart north – south between 66-67° 30' N and 2° E – 4° W. Continuous acoustic recordings of fish and plankton were made by a calibrated (after Foote, 1987) echo integration unit consisting of a 38kHz Simrad EK500, connected to a Bergen Echo Integrator (BEI) (Knudsen, 1990) for post-processing of the recordings and allocation of backscattering strength (S_A) to species, on the basis of the proportion of different species caught at trawl stations, target strength distribution, and fish behaviour. The S_A (used as a proxy for relative school size) of individual herring schools was

determined by using the school box option in the BEI system (Figure 2.1a). Appendix 2.1.1 provides technical details on settings of acoustic instruments.

A 95kHz Simrad SA950 sonar was used to determine the spatial distribution of schools at a range 50-500m to the side of the vessel, and to track selected herring schools for periods of up to one hour (Figure 2.1b, Appendix 2.1.2). Data was output to computer file and colour coded paper echogram. The sonar was connected to a HP 9000 workstation with software for the detection and measurements of school area (m^2) and relative density (measured as colour sum units; an expression of the relative echo intensity (Misund et al. 1997) that is directly related to the relative density of a school (Misund pers. comm)). Only those data log periods previously judged as herring from echosounder data, were used for analysis. Four periods of recordings were identified, for each of which confirmation of individual schools was later obtained by visual judging of paper echograms. During tracking, behavioural events of schools were noted continuously by a reporter and also recorded on video for later analysis. Behaviours were classified into two categories; intra- and inter-school events using the descriptions according to Pitcher et al. (1996) (Appendix 2.1.3).

Pelagic trawl samples (Åkra-trawl) were taken to identify acoustic targets. By modification of bridle and warp length and use of large floats on the doors, the trawl can be rigged to catch deep (100-400 m) or shallow (0-50 m) schools (Valdemarsen and Misund, 1994). Sub-samples of up to 100 specimens of herring were taken from each trawl catch. Length, weight, age (from scales), sex, maturation stage and stomach content were recorded using standard procedures and notation of the Institute of Marine Research (IMR), Bergen (Appendix 2.1.4).

During the cruise, a new protocol was devised for conducting small meso-scale surveys of school distribution. Immediately after an individual school was tracked, the vessel surveyed the surrounding area by running a cruise track of increasing concentric rings. The radius of the outermost ring was approximately 1.2 km. Although it is possible to use way points plotted on the automatic navigation system to aid control of the cruise track, we consider in hindsight that it is more convenient to run straight cruise tracks creating squares of increasing width (Figure 2.2). Three meso-scale surveys were completed, but due to poor weather conditions for sonar operation the mapping was unsuccessful. Description here serves to outline the new protocol.

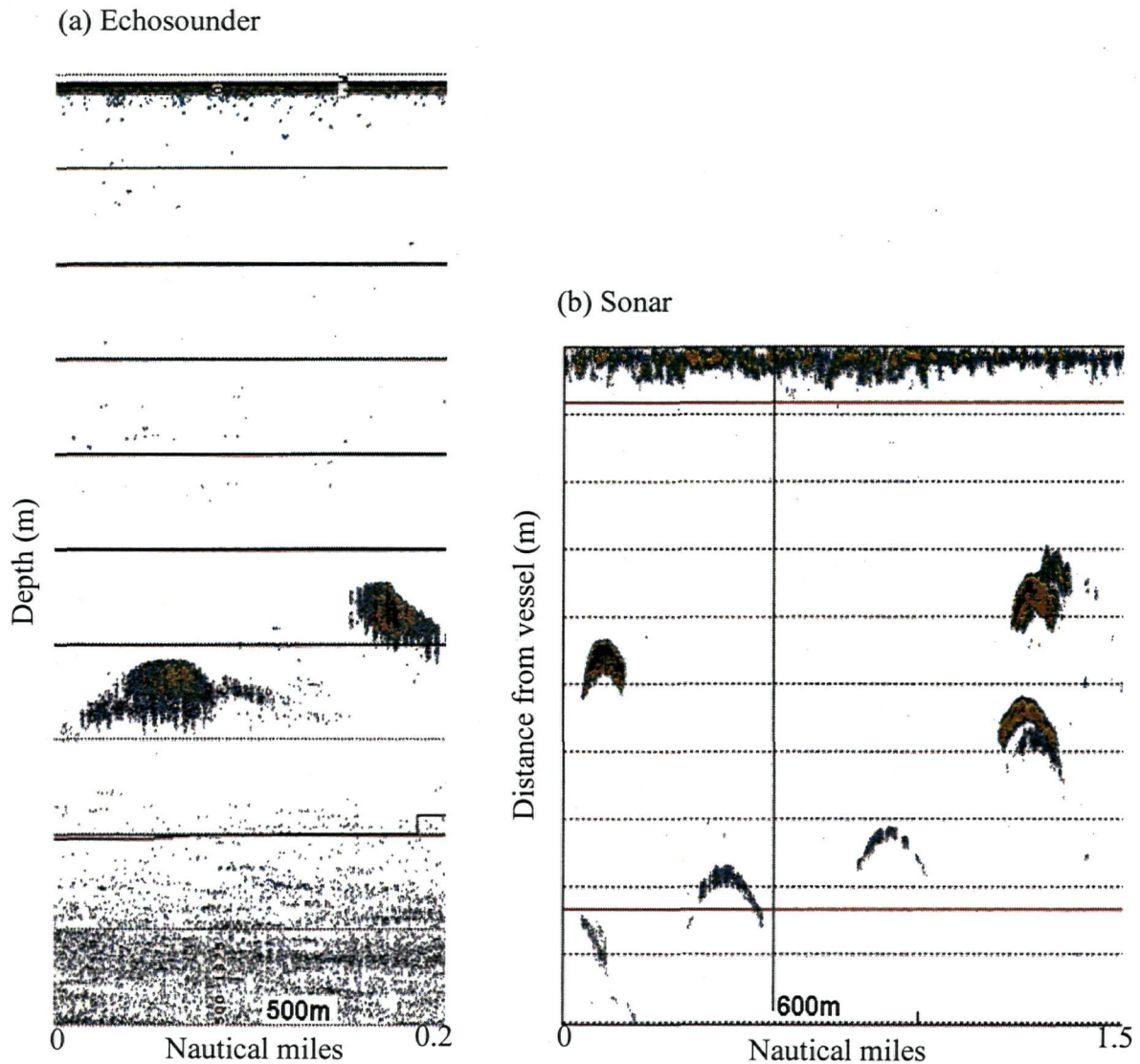


Figure 2.1 Recordings of herring schools by the (a) EK-500 echosounder: vertical axis is water depth, distance between solid horizontal lines is 50m and maximum depth is 500m. (b) SIMRAD SA950 sonar: The sonar is tilted -5° and directed 90° port. The dotted horizontal lines are spaced 60 m apart with the highest part of the figure closest to the ship. Only schools falling between 50-500m (solid horizontal lines) were recorded for the survey, since beyond that reliability of measurements become limited. There is no relation between the signals and the actual school shape. The shape of the signals is due to the change in distance between the vessel and the school when the vessel passes the school.

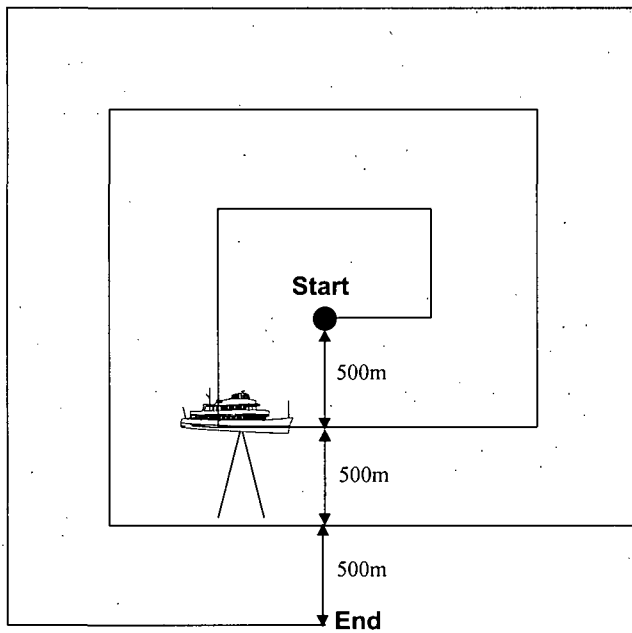


Figure 2.2. Meso-scale mapping of herring schools

The ratio of mean nearest neighbour distance (*NND*; two-dimensional distance from a school to its closest neighbour school) to the mean average inter-school distance (\overline{ISD} ; where \overline{ISD} = average two-dimensional distance of a school to all other schools) serves as a useful descriptive index providing information on the meso-scale pattern of school clustering, viz;

‘Cluster Ratio’ is the comparison of $meanNND : mean\overline{ISD}$

$$\text{where, } meanNND = \frac{\sum_{i=1}^n NND}{n} \quad \text{and} \quad mean\overline{ISD} = \frac{\sum_{i=1}^n \overline{ISD}}{n}$$

and n = number of schools

Alone, each statistic tells us small pieces of information. By quantifying the mean distance among all schools, the \overline{ISD} tells us about the area over which all schools are distributed relative to the extent of the survey area; it provides information on the scale of observation and is dependent on the observation tool. Mean *NND* tells us how close schools in a cluster are. The ratio of the two descriptors, $meanNND : mean\overline{ISD}$, provides us with a more functional comparative distribution index. Not only does it allow us to deduce facts about spatial scale, it provides insight into the intensity and pattern of school clustering (Figure 2.3).

If we reduce the ratio to the coefficient;

$$\text{Cluster coefficient} = \frac{meanNND}{mean\overline{ISD}}$$

we lose the information on scale but still retain an impression of what the overall pattern and degree of clustering is like. Cluster coefficient (CC) values can range from 0 to 1 but are likely to be the lower end of this scale, since it is rare that mean \overline{ISD} distance would be close to or equal mean NND. A low CC value (mean NND low and mean \overline{ISD} high) would suggest that individual schools in close proximity are tightly clustered whilst those clusters are dispersed (Box 1, Figure 2.3). A CC close to 1 suggests many schools are diffuse, not forming strong clusters (Box 9, Figure 2.3).

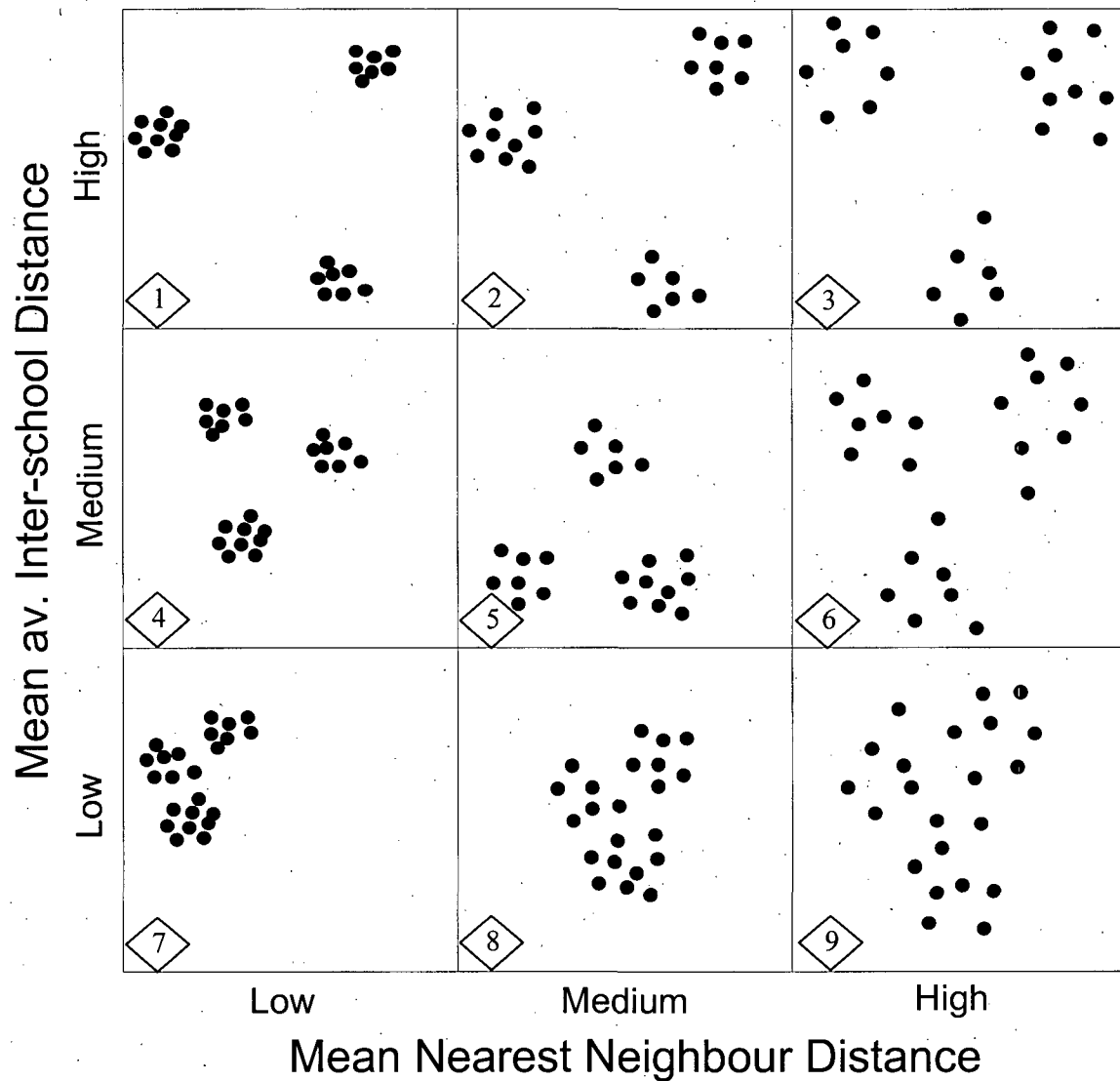


Figure 2.3 Schematic representation of hypothetical patterns of school clustering indicated by relationships between mean NND (distance to closest neighbour school) and mean \overline{ISD} (mean of the average distance among all schools). Both parameters measure two-dimensional distance between schools.

RESULTS

Herring were recorded mainly between $65^{\circ}30'$ - $67^{\circ}30'$ N, $003^{\circ}30'$ W- 002° E as confirmed from samples of nine trawl stations. Average size ranged from 30.4 to 33.8 cm with a tendency for larger herring to be found in catches from the south western area (IMR, 1997). Within all samples, herring were recovering from spawning (mean gonad score: 7.8, spent to recovering), had a low fat content (mean fat index: 1.2, none to little) and were confirmed to be actively feeding (mean gut fullness index: 3.3, medium to full).

LARGE MESO-SCALE OBSERVATIONS

School structure characteristics

A total of 285 herring schools were recorded by echosounder (Figure 2.4), 52 percent of which were recorded during darkness. In comparison, 604 schools were recorded by side-scan sonar over four short periods of observation, during which time the echosounder recorded only 62 schools.

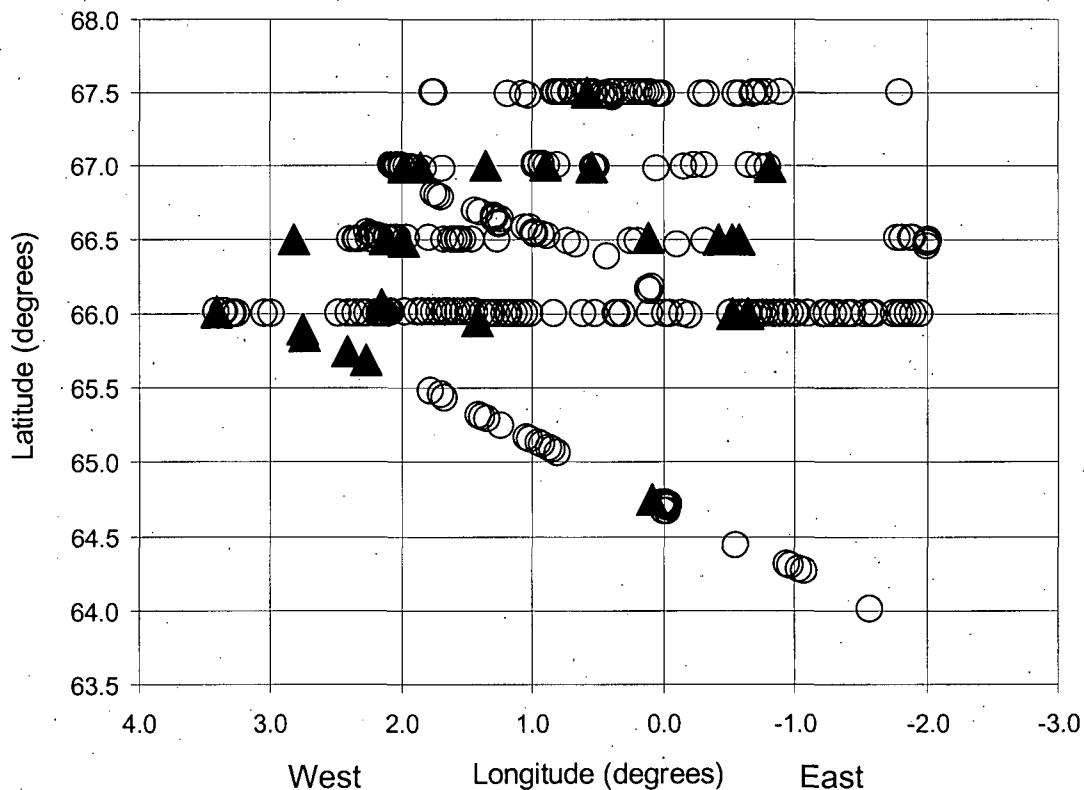


Figure 2.4 Distribution of herring schools in the Norwegian Sea recorded by EK500 echosounder (circles) (8/4/97-18/4/97) and locations of individual school tracking using sonar (solid triangles). After each tracking, trawl samples were taken to identify acoustic targets.

Using the area back-scattering strength (S_A -value) as a proxy for relative school size, individual schools were grouped into size categories (Figure 2.5). Very small, small and medium sized school were most numerous (83%) but only accounted for approximately one third of the total relative size ($\sum S_A$ -values).

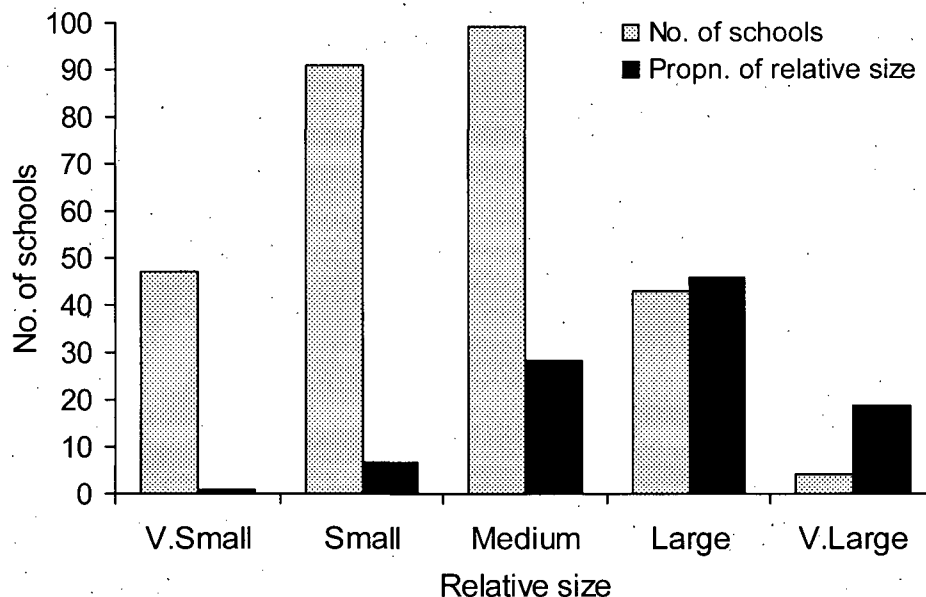


Figure 2.5 Size class frequencies and proportional contribution to total relative size (S_A -value) of echosounder recorded schools. Relative size classes based on area back-scattering coefficient (S_A -value): Very small <50, Small 50-250, Medium 251-1000, Large 1001-5000, Very Large >5000.

Of those schools recorded by sonar, the area of most was between 50 and 200 m^2 with a low relative density of approximately 500 colour sum units (Figure 2.6 and 2.7). Using an empirical relationship published by Misund et al. (1996) the biomass of herring shoals recorded by the SA950 sonar can be estimated from the area of the school (Biomass (t) = $18.4 \times \text{Area (m}^2\text{)}$). Using this formula, the average school biomass recorded during this survey was estimated to be 1969 kg, approximately 2 tonnes.

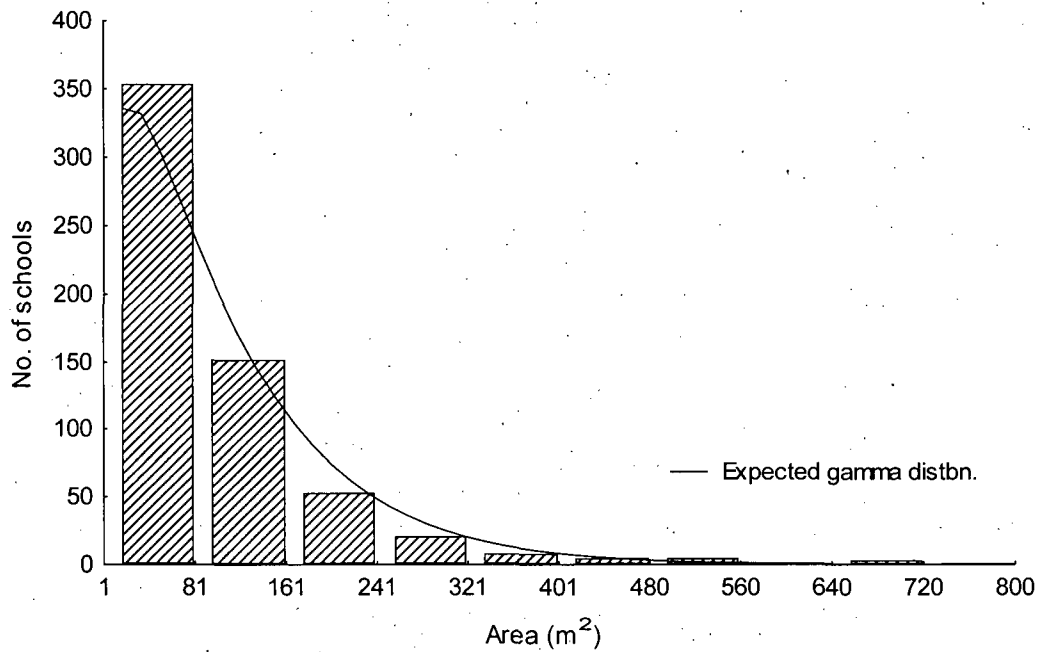


Figure 2.6 Frequency distribution of school area. A gamma distribution (scale parameter: 83, shape parameter: 1.28) is fitted to the data, although the observed data are significantly different from that expected ($n = 604$, $\chi^2=32.55$, $df = 3$ (adjusted), $p = <0.0001$) because of the high number of observations.

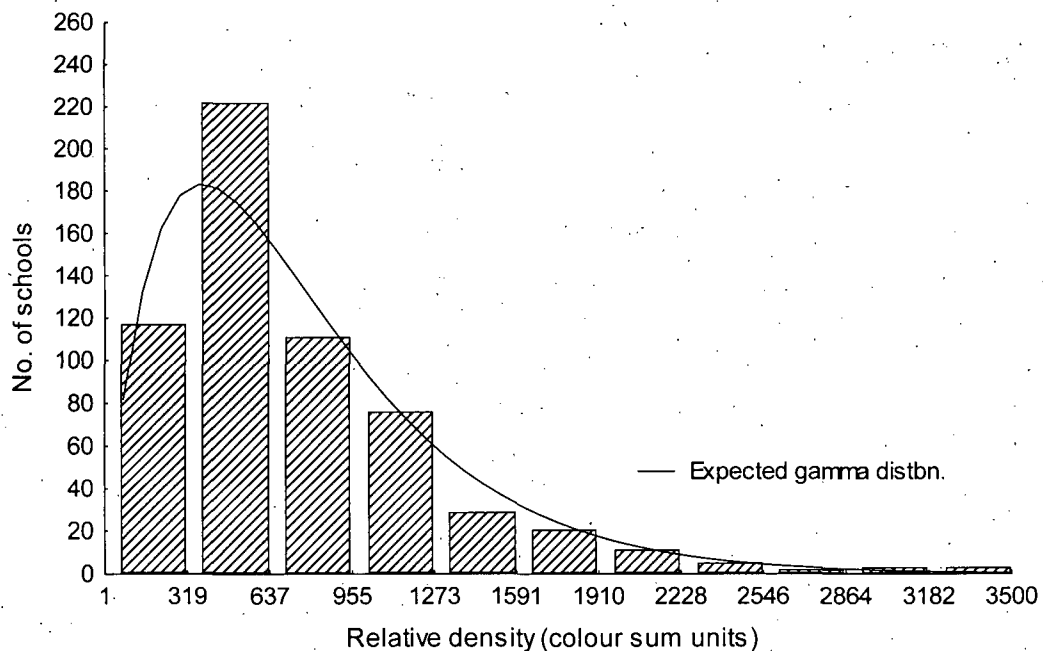


Figure 2.7 Frequency distribution of school relative density. Relative density scale runs from high on right hand side to low on left hand side. A gamma distribution (scale parameter: 389, shape parameter: 1.97) is fitted to the data, although the observed data are significantly different from that expected ($n = 604$, $\chi^2=30.77$, $df = 6$ (adjusted), $p = <0.0001$) because of the high number of observations.

Spatial distribution pattern

Nearest neighbour distance (NND) distributions suggest two spatial scales of clustering; (i) Echosounder data indicates a high occurrence of schools within 0.8-2.5 km of each other (Figure 2.8a), (ii) Sonar data shows a high number of schools with NND between 0.05-0.3 km (Figure 2.8b). Based simply on detection capabilities (volume coverage), it is unsurprising that sonar results suggest a finer scale of spatial pattern. Also noteworthy is the occurrence of a few seemingly isolated schools with NND 8-35km as detected by the echosounder. In addition to highlighting these isolated schools, cluster analysis of schools recorded by echosounder provides supporting evidence for the scale of clustering determined from the NND distributions. From visual inspection of Figure 2.9, linkage of schools by nearest neighbour reveals most clustering occurs on a scale of 0.5 to 2 km.

The distribution of cluster coefficient (NND/\overline{ISD}) values for individual schools can be used to describe their intensity of clustering and thus is more informative than the distribution of NND alone. Giving consideration to the distribution of NND (Figure 2.8) our interpretation of Figure 2.10 is that individual schools are aggregated into intense clusters and these clusters appear to be patchily distributed (a pattern similar to Box 1, Figure 2.3). Furthermore, comparison of the sonar and echosounder mean NND, mean \overline{ISD} and cluster coefficient values, confirms that despite differences in detection capabilities of sonar and echosounder, there is similarity in the pattern of school clustering across scales (Table 2.1).

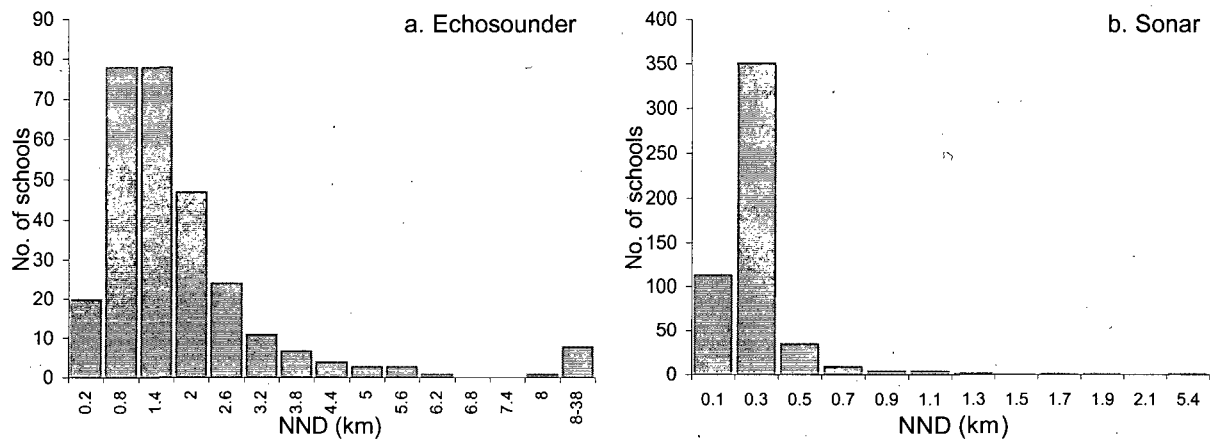


Figure 2.8 Distribution of NND.

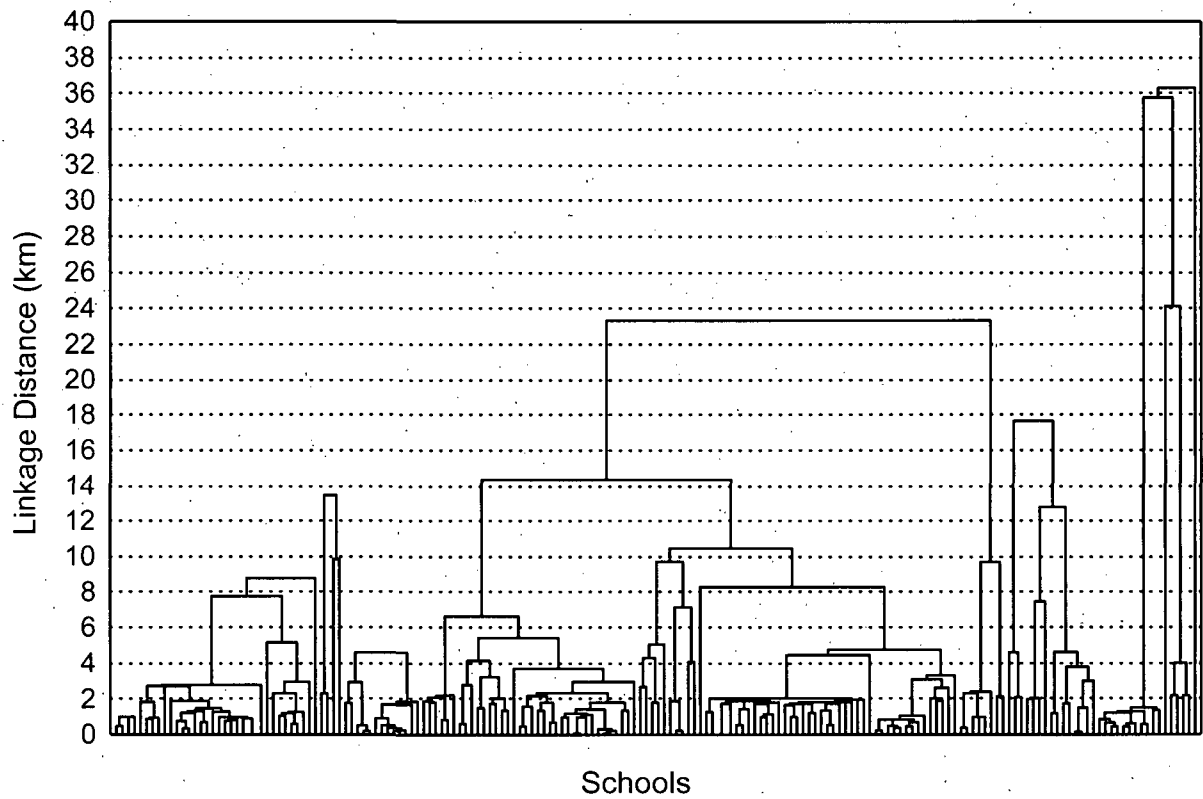


Figure 2.9 Cluster analysis tree, derived from a matrix of distances between schools recorded by echosounder. Linked using single linkage (nearest neighbour) basis. Many linkages occur at low distances (0.5-2km) indicating tight clustering of schools at this scale. Schools on extreme right have highest linkage distance, being more isolated from other clusters.

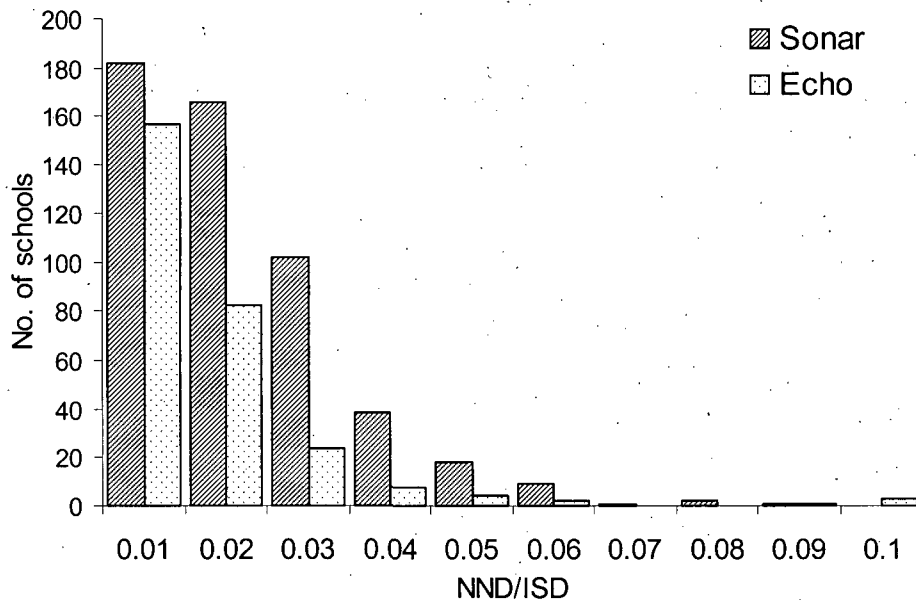


Figure 2.10 Distribution of cluster coefficient values

Table 2.1 Comparison of school distribution parameters

	mean NND (km)	mean \overline{ISD} (km)	Cluster coefficient
Echosounder	1.83	127.8	0.0141
Sonar	0.163	11.62	0.0143

Spatial distribution by size

Both frequency of occurrence with, and average distance to other surrounding schools were found to vary with school size. Firstly, for certain school sizes there was significant difference in frequencies of occurrence with neighbour schools of a particular size ($\chi^2=41.37$, $df=16$, $p<0.001$, Table 2.2). In particular, small schools had other small and very small schools as nearest neighbour more often than expected by random chance, whilst medium and large schools were their neighbours less often than expected. Combinations of very large, large and medium schools occurred as neighbours appreciably more often than expected. Secondly, average distance between schools increased with school size, small schools being closer to other schools than large schools were ($\chi^2=11.82$, $df=4$, $p<0.02$) i.e. small schools were more tightly clustered than large ones (Figure 2.11). However, school size did not specifically determine the distance to nearest neighbour; when a size classified distribution of nearest neighbours was produced, it did not differ significantly from what may be expected by chance ($\chi^2=60.7$, $df=48$, $p>0.11$).

Table 2.2 Observed and expected frequencies of occurrence of schools of certain sizes as nearest neighbours.

<i>Observed frequencies (Expected frequencies)</i>					
	V.small	Small	Medium	Large	V.Large
V.small	7 (7)				
Small	43 (30)	40 (30)			
Medium	25 (32)	53 (65)	39 (35)		
Large	9 (13)	10 (27)	37 (29)	12 (6)	
V.Large	1 (2)	0 (3)	5 (3)	3 (1)	0 (0.1)

Diurnal temporal variation in pattern and distribution

An attempt was made to see if there was any temporal difference in clustering pattern of schools between day and night. To do so, it is necessary to remove as far as possible the differences due to spatial variation. Accordingly, we focused the analysis on discrete data periods in which schools were continuously recorded and where there were approximately the same number of schools recorded during day and night. Individual schools were found to be significantly more tightly aggregated during the night than day (Table 2.3), and as schools became more clustered at night, the extent or range of school clusters (indicated by mean \overline{ISD}) declined significantly also (Table 2.3). The cluster coefficient is no different between day and night for the echosounder, whilst it is more than double for the sonar. This implies that changes in the pattern of clustering was only observed on the finer scale; individual schools being closer together at night, whilst clusters were less patchy than in the day.

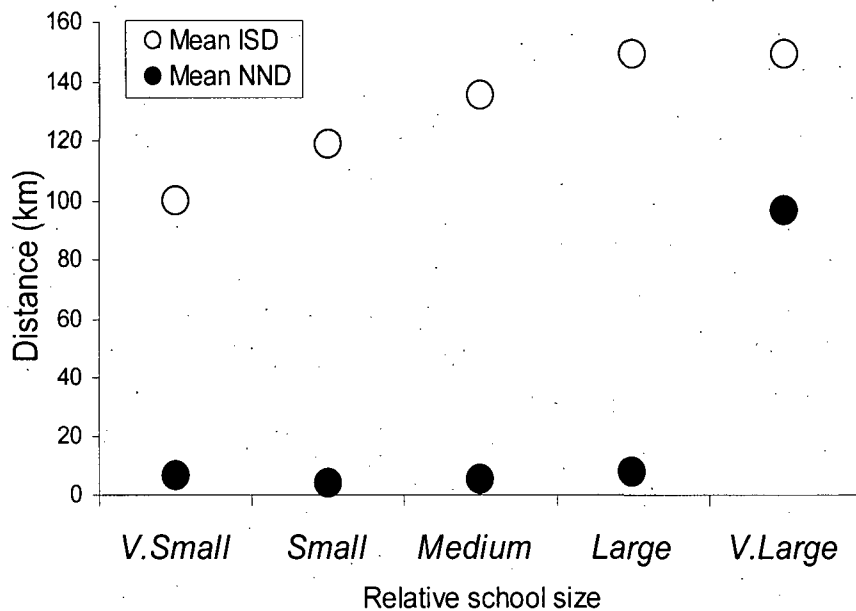


Figure 2.11 Relationships between average nearest neighbour distance (mean NND), mean average inter-school distance (mean \overline{ISD}) and school size for echosounder data.

Table 2.3 Differences in diurnal distribution pattern. Standard errors are given in brackets. Note: ^a one tailed t-test with unequal variances; ^b one tailed t-tests with equal variances.

		Day	Night	Significance
Echosounder	Mean NND (km)	4.5 (0.75)	2.8 (0.33)	^a $P < 0.05$
	Mean \overline{ISD} (km)	95.6 (4.55)	56.5 (2.37)	^a $P < 0.001$
	n	54	35	
	Cluster coeff.	0.047	0.050	^b Not signif.
Sonar	Mean NND (km)	0.4 (0.06)	0.1 (0.004)	^a $P < 0.001$
	Mean \overline{ISD} (km)	33.5 (1.08)	2.9 (0.06)	^a $P < 0.001$
	n	132	138	
	Cluster coeff.	0.011	0.024	^b $P < 0.001$

Within clusters, a typical strong diurnal vertical migration was observed, the majority of schools rising to shallow water during the night and diving to deep water during the day (Figure 2.12a). Both echosounder and sonar data showed depth of schools was significantly deeper during the day than night; (i) Echosounder: (One tailed t-test, $t=15.13$, $df=260$, $p<0.0001$; Figure 2.12b), (ii) Sonar: many more schools were detected during the night (78%) and were significantly shallower than daytime schools (One tailed t-test, $t=15.6$, $df=147$, $p<0.0001$, Figure 2.13). Although not statistically significant, mean relative density of night schools (746 colour sum units) was appreciably lower than daytime schools (848 colour sum units). No difference was detected in the area or the relative size of schools. Daytime schools were also distributed through a greater depth range.

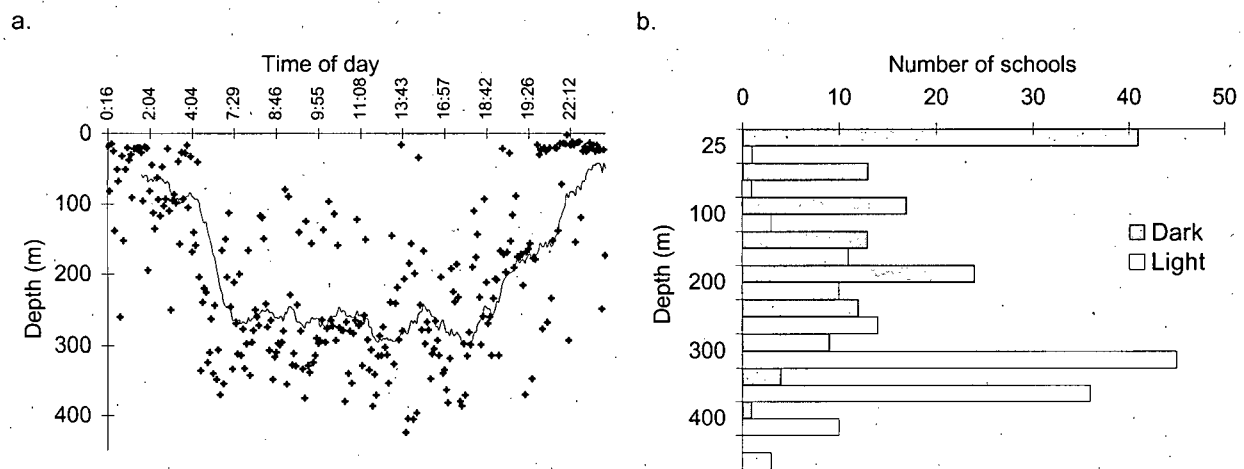


Figure 2.12 Diurnal changes in vertical distribution recorded by echosounder. a) depth distribution with 20 point running average line plotted on figure, b) number of shoals recorded at each depth

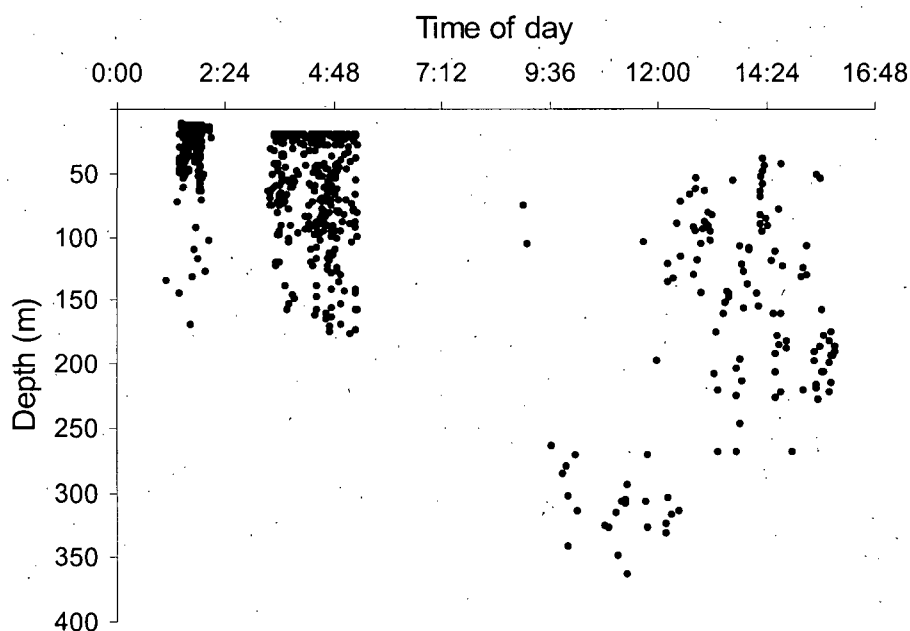


Figure 2.13 Diurnal depth of distribution of sonar recorded schools. Note: the four distinct groups relate to four separate data log periods.

SMALL MESO-SCALE OBSERVATIONS

Behavioural dynamics

One hundred and four behavioural events were recorded from 31 herring schools tracked by sonar for an average of 40 min each, giving a total of 20 hours and 41 minutes total observation time. Some kind of change in school behaviour occurred every 11.9 min. ($n=104$, 95% CL:0-26). Behavioural events (Appendix 2.1.3) were classified into two categories. *Inter-school* (between schools) events occurred every 29 min ($n=50$; 95% CL:5-54). *Intra-school* (within a school)

events occurred every 25 min ($n=50$; 95% CL:0-52). The distribution of total events per hour (event rate) provides a guide for classifying the overall dynamics of the schools observed. This descriptor, which we have called dynamic tendency, is a measure of the propensity for schools to move, split, join or change shape. Note that the dynamic tendency is significantly higher during the night than day (Figure 2.14). This point is born out in greater detail in Figure 2.15 b-c which show intervals between behavioural events within each category. Most events occurred more frequently during the night than day. In particular, schools were observed more frequently changing shape, surfacing, joining, leaving and splitting. Although the data do not support close scrutiny it is noteworthy that dusk appears to be a very active period. Of those intra-school events occurring at night only 15% of joins occurred at dusk, whereas 54% of splits and 100% of leaves were observed in this period.

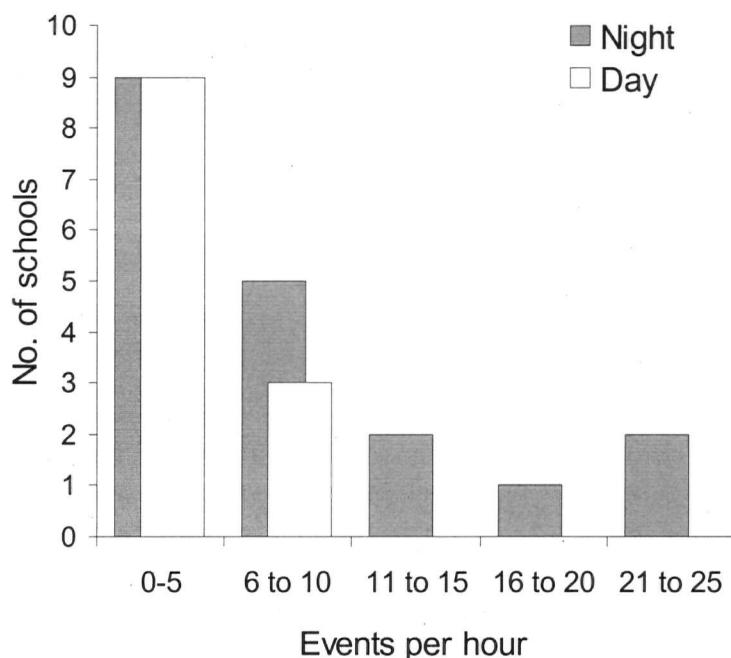


Figure 2.14 Distribution of behaviour events

DISCUSSION

During April 1997, macro-scale distribution of ocean-feeding Norwegian spring spawning herring was centred around a cold front region mainly between $65^{\circ}30' - 67^{\circ}30' \text{ N}$, $003^{\circ}30' \text{ W} - 002^{\circ} \text{ E}$. At the cold front, warm Atlantic water rising northwards meets with cool polar water travelling south. The front is characterised by a sharp decline in temperature together with high concentrations of zooplankton (Blindheim, 1989). We presume the cold front offers profitable foraging on zooplankton for actively feeding herring that are highly motivated by hunger following the non-feeding periods of overwintering and spawning (Slotte, 1996; Nøttestad et al. 1996, Fernö et al. 1998).

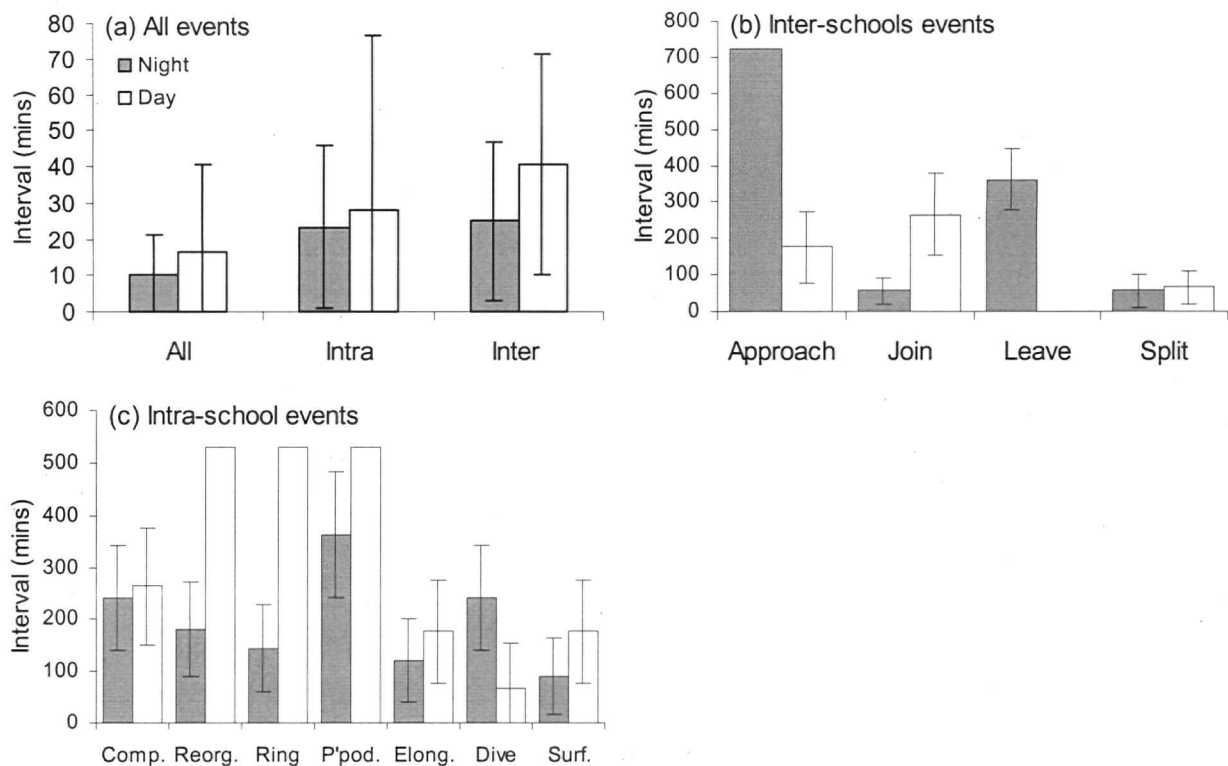


Figure 2.15 Behavioural event intervals of tracked schools. No error bars are displayed for events recorded less than twice. Abbreviations of behavioural events (see Appendix 2.1.3 for detailed descriptions): Comp. – compact; Reorg. – reorganise; P'pod. – pseudopodium; Elong. – elongate; Surf. – surface; Ring - ring structure.

Within the region, two levels of meso-scale distribution were observed, one at 0.05 to 0.3 km recorded by sonar and another at 0.8 to 2.5 km recorded by echosounder. According to the cluster ratio, (mean NND :mean \overline{ISD} ; a relative measure of the intensity and pattern of clustering), both scales indicated a patchy distribution of intensely clustered schools. Furthermore, despite differences in detection capabilities of sonar and echosounders as a result differences in sampling volume (Misund et al. 1996; Misund, 1997), pattern of distribution was similar between scales, as revealed by comparison of cluster coefficients. By identifying and characterising changes in the dispersion pattern of schools, the cluster ratio offers a descriptive index to make comparisons between surveys conducted in different places and at different seasons.

Within clusters, the majority of schools (83%) recorded by echosounder were categorised as very small to medium size, and most of those recorded by sonar were between 50 to 200 m² (mean 107 m²) with an equivalent biomass estimated at 0.9 to 3.7 t (mean 1.96 t). Tokarev (1958, in Radakov, 1973) similarly noted that foraging Atlantic herring occurred predominantly as small schools with diameter 1-20m and average height 2-7m, with the largest rarely extending >50m. Average school size for herring during overwintering and pre-spawning life history stages is

generally much larger (Winters, 1977; McCarter et al. 1994; Wood, 1930; Nøttestad et al. 1996, Mackinson, 1999b).

The school area-to-school biomass relationship used to convert the sonar recording to biomass (Misund et al. 1969) was established for North Sea herring schooling shallower than 150 m, and to use the same relationship for the deep swimming schools in the Norwegian Sea may not be valid. This is especially because the sonar projection of the schools at great depth in daytime (down to about 350 m) may be a substantial underestimate of the true horizontal extent.

Small and very small schools were more tightly clustered than medium or large schools and occurred as neighbours more frequently than would be expected by chance alone. Close proximity provides small schools possibilities for rapid size adjustment through splitting and joining, and thus individuals achieve benefits of flexibility of responses to their dynamic environment. Whilst hunger reduces school cohesiveness (Morgan, 1988; Robinson and Pitcher, 1989) and active feeding may result in complete splitting of schools in to smaller units (Keenlyside, 1955), anti-predator advantages associated with larger school size (in particular dilution) are diminished (Magurran, 1990). However, intense clustering of schools combined with a dynamic adjustment regime may enable schools to maintain 'collective' vigilance whilst simultaneously receiving the foraging benefits associated with smaller schools (Pitcher and Parrish, 1993). Indeed, our small meso-scale behavioural observations support the contention that observed dynamic adjustments among schools may aid transfer of information about their surroundings. Inter-school events, the most frequent of which was joining and splitting, occurred on average every 29 mins.

As might be expected and as previously observed by Pitcher et al. (1996), intra-school events including changes in shape and density of individual schools occurred more frequently than behavioural events among schools. Although in this survey we did not observe any direct evidence of herring predators (in part due to exceptionally poor surface observation conditions), they are known to abound in the survey region. If herring opt for a precautionary approach and behave as if attack from predators is likely (Lima and Dill, 1990) even if it seldom occurs, this may have an important effect on distribution, school size and behaviour dynamics.

The few recorded large schools occurred as neighbours more frequently than expected yet were more isolated with respect to other schools. Distance to nearest neighbour was higher and their average distance to all other schools also higher. Occurrence of dense food patches may in part explain the more diffuse distribution of large schools. When food is very abundant there is likely a threshold beyond which no foraging benefit is gained from splitting and leaving a school. Reduced competition may allow for the persistence of larger schools. The range of school sizes observed lends supporting evidence to this. An alternative suggestion is that these larger schools are migrating schools that are somehow distinct from those classified as feeding as observed by Nøttestad et al. (1996). Larkin and Walton (1969) presented theoretical evidence suggesting

large school size is more efficient for migrating to a specific point since the error in navigation is reduced.

A considerable amount of variation in structure and distribution of herring schools can be attributed to scale changes associated with diurnal migration. Changes in depth distribution of many schools displayed a typical vertical migration, presumably as herring moved with their food. However, some schools remained deep (300 m) even at night. Although there was no apparent difference in school size, density of schools was appreciably lower at night and we assume this to be a direct result of feeding activity (Pitcher and Partridge, 1979; Morgan, 1988; Robinson and Pitcher, 1989) and reduced light level (Radakov, 1973; Blaxter and Hunter, 1982). Yudovich (1954, *in* Radakov, 1973) recorded a packing density of 0.6-0.7 kg per m³ (equivalent to approximately 2 fish per m³ for 30 cm herring) in foraging Atlantic herring. Comparison of distribution of NND and \overline{ISD} for individual schools indicate that on both scales, 0.05 to 0.3 km and 0.8 to 2.5 km, schools are closer together, and the range of clusters is significantly reduced at night. The pattern of school clustering is also significantly different at the lower scale; clusters being relatively less patchy. The observation that many more schools were detected by sonar during the night may in part be accounted for by the sonars' reduced detection of deep swimming schools during daytime.

The dynamic tendency of individual schools was significantly higher at night than during the day. In particular, shape of schools together with splitting and joining events occurred much more frequently at night, presumably reflecting the dynamics associated with active feeding. Much activity associated with change in school size occurred specifically at dusk. Although some of the events recorded by sonar can be attributed to varying degrees of distortion (Misund et al. 1997), rapid changes in tilt angle distribution associated with feeding might account for the observed dynamics, particularly changes in school shape. Moreover, the observations support our contention that the dynamics reflect a regime of rapidly changing individual behavioural decisions.

Although herring are known on occasion to exhibit strong avoidance reactions to near field vessel sounds (Olsen et al. 1983; Misund, 1997), we do not consider this to have biased our observations for several reasons (i) during daytime schools tend to swim at great depth (up to 500m); (ii) behavioural observations were made by sonar on schools at a considerable distance from the vessel and for relatively long observation periods; (iii) low vessel speed (1-3 knots) and hence noise, is unlikely to elicit a strong avoidance response; (iv) herring are known to display reduced reaction during this season (Mohr, 1971) probably as a result of heightened feeding motivation.

Given the significant energetic costs of performing diurnal vertical migrations, the benefit should necessarily exceed these costs. Several studies point to multiple causality with trade-offs occurring among factors including feeding, temperature optimisation and predator avoidance

(Neilson and Perry, 1990; Olla and Davis, 1990; Sogard and Olla, 1993; Brodeur and Wilson, 1996). Herring that choose not to perform diurnal vertical migrations may have feeding opportunities in deep, cold water where food can also be abundant (Melle et al., 1994). Vertical migration to below a thermocline can be stimulated by feeding opportunity (Brodeur and Wilson, 1996; Galaktionov, 1984), particularly if food is limited above the thermocline (Bailey, 1989). When prey availability was low, 0-group walleye pollock accrued an energetic advantage from diel migration to cold water since growth was enhanced through exposure to low temperatures (Smith et al. 1986). Risk of predation may provide additional motivation for preventing the herring from performing vertical migration. In lab experiments, juvenile pollock generally remained above a thermocline but were motivated to go below when food was introduced below or a predator from above (Olla and Davis, 1990; Sogard and Olla, 1993). Furthermore, very deep water may present a physiological limit to potential predators, thus providing a safe haven for herring. For migrating fish, lower temperatures and deep currents may also confer energy saving advantages.

Spatial and temporal variation is partly a function of the size of window used to view the world (Levin, 1992), and thus our description of the system will vary with the choice of scales. In this study our tools, echosounder and sonar, provide the window. Recognising limitations associated with both the use and interpretation of these methods (Misund, 1997), they have nevertheless provided insight to two scales of spatial pattern of herring schools and provided important understanding of how the system description changes among scales. The use of fractals (e.g. Sugihara and May, 1990) may help provide fuller insight. At some scales, responses of herring occur to a narrow range of stimuli (e.g. predator attacks) while others are diffusely linked to a broad range of conditions such as food distribution and temperature gradients. Correlations of the distribution of avian predators and schooling fish have been shown to be scale-dependent, not simply a reflection of each others general distribution (Schneider and Piatt, 1986; Schneider, 1989). Since we have no direct evidence of predators, we conclude that for the most part, activity motivated by feeding opportunities is the primary behaviour giving rise to the observed variability in distribution, structure and dynamics of herring schools in the Norwegian Sea during early spring.

2.2 Variation in structure and distribution of pre-spawning Pacific herring shoals in two regions of British Columbia².

INTRODUCTION

Herring *Clupea harengus* L. are thought to adopt a 'preferred conservative life strategy' (Fernö et al. 1998). Simply stated, this means that herring attempt to follow the line of least resistance through the obstacles of life. Avoiding risk of predation, they strive to maximise feeding and reproductive opportunities. Seasonal changes in the motivational and physiological state of individual fish drives their annual life path between feeding, overwintering and spawning grounds. Pasted on to this backdrop of life history, individual behavioural responses compensate for meso-scale variation in external influences (e.g. oceanographic conditions, distribution and abundance of food and predators), diverting the herring from their preferred path of least resistance. The result is manifest as localised temporal and spatial changes in the structure and distribution of shoals (*sensu* Pitcher, 1983). In the words of Radakov (1973), "the character of the shoal is that of a labile adaptation to changeable conditions".

Studying the factors influencing changes in the spatio-temporal distribution of fish not only elucidates the evolutionary and ecological basis of adaptive behaviour; it is critical to successful fisheries management. Failure to recognise spatial complexity has resulted in stock collapses in the past (Walters & Maguire, 1996). In particular, there are two reasons why a better understanding of shoal structure and dynamics is required: (i) schooling behaviour can result in sharp increases in catchability (Schaaf, 1980; Winters & Wheeler, 1985; Csirke, 1989) leading to stock collapse (Pitcher, 1996; Mackinson et al. 1997a); and (ii) knowledge of the factors driving movements and behaviour of herring is a pre-requisite for the development of harvest control strategies based on exposure limitation principles, whereby fishing areas and times are set so that only the desired proportion of the stock is exposed to exploitation.

Morgan (1988) stated that shoal structure changes in a qualitatively predictable way when certain conditions change. By comparing the variation in structure and meso-scale distribution of shoals in two contrasting regions of British Columbia, Canada, this study endeavours to show how both internal state (maturation) and behavioural adaptation to local external forces (predators and oceanographic conditions) act in concert to produce the observed distribution of pre-spawning Pacific herring *Clupea harengus pallasii* shoals. The work presents the first detailed spatial analysis of pre-spawning Pacific herring shoals in two fisheries management regions of British Columbia; the Strait of Georgia and Central Coast.

² Parts of the work contained in this section have been the basis of a publication, Mackinson. (1999b)

MATERIALS AND METHODS

Data on herring shoals were collected between 27th February and 9th March 1997, in the Strait of Georgia (SoG) (49°N, 123°W) and 2nd-28th March 1998, in the Central Coast (CC) (52°N, 128°W). Chartered for the Department of Fisheries and Oceans (DFO) annual pre-fishery roe-herring survey, the seine fishing vessel, "Kynoc", was the research platform for both surveys.

Shoals were detected by sonar, echosounders and visually, using the presence of birds and sea mammals as indicators. Once detected, the vessel approached each shoal and passed over with the echosounder, during which the following measurements were taken:

1. time of detection - time when the first trace appeared on sounder
2. accurate location - latitude and longitude marked on a computerised nautical chart
3. bottom depth - total water depth in which shoals occurred
4. vertical extent - height of shoal in metres
5. estimate of the shoal biomass³
6. estimate of relative packing density³ - five point scale based on colour
7. shape of shoals - later classified into nine groups (Table 2.4)

Table 2.4. Classification of shoal shapes.

Shape	Description
Streak	Vertically extended, the base of shoal not touching the bottom. Height typically 4 times greater than width
Layer	Continuous layer/band of fish at uniform depth and spanning the sounder screen
Bottom amorphous	Sitting on the bottom associated with a feature
Column	Height >2 times width, and base touching floor
Bottom pod	Rounded compact shoal sitting on bottom
Spherical	Rounded shoal in mid water
Scratch/dab	Very small marks on sounder appearing as scratches or dots
Skimmer	Night time diffuse layer
Amorphous	Irregular structure

8. detailed notes and sketches to show particular features of shoals (on several occasions, still pictures of acoustic outputs were taken)
9. relative abundance of predators in occurrence with herring shoals
10. stomach contents of sub-samples of herring

³ Visually judged by skipper. This method is respected and relied upon in the roe-herring pre-fishery surveys. It is not possible for the researcher to develop the ability to judge biomass or relative density visually on a consistent basis within the period, so the skipper's estimate was used. The same approach was used by Hewitt et al., (1976).

In addition to the above field recordings, the following parameters were calculated for each shoal:

11. relative depth - the midpoint of the shoal expressed as a percentage of water depth
12. relative height (index of vertical extension) - the height of the shoal expressed as a percentage of water depth
13. mean nearest neighbour distances between shoals (mean NND) (Fig. 2.16a)
14. mean of the average distance among all shoals (mean \overline{ISD} ; Inter-Shoal Distance) (Fig. 2.16b).

The cruise track was determined solely by the skipper. No measurements were taken of shoals not recorded by the echosounder.

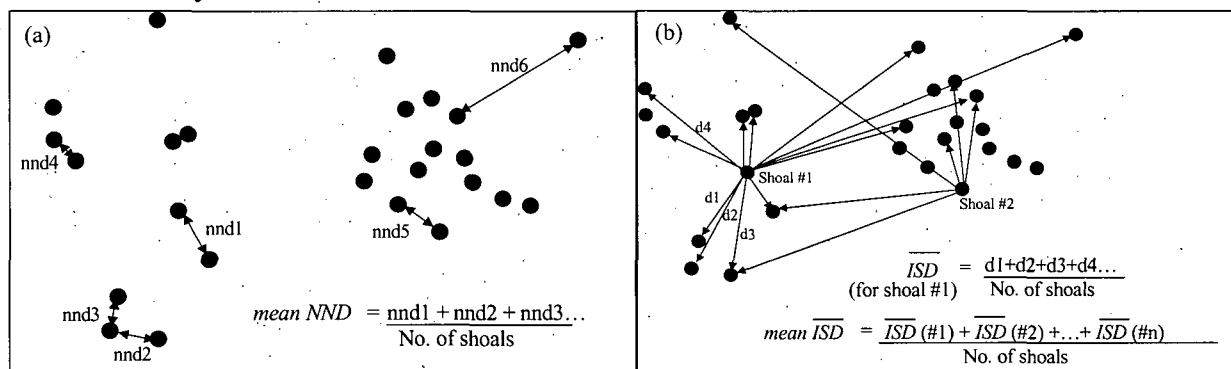


Figure 2.16. Calculation of mean NND and mean \overline{ISD} .

Acoustic targets were verified as herring by directed seine netting on representative shoals. Biological samples were taken in accordance with the charter vessel survey program (Armstrong, 1986). Briefly, this involved taking samples to determine length frequencies, maturation condition and sex ratio. The maturation stage of female gonads was divided into three industry defined categories (Table 2.5). Catch data from logbooks of all survey vessels were supplied by the DFO and are used in the analysis here.

RESULTS

One hundred and seventy five recordings of shoals were made in the SoG and 555 shoals in the CC. Approximately 70 shoals in SoG and 257 in CC were considered to be repeated recordings since several areas were surveyed on more than one occasion. Repeated recordings were not used in calculations of the distribution parameters; mean NND and mean \overline{ISD} .

Table 2.5. Comparison of maturity stages of BC roe-herring industry and those described by (Hay, 1985). Industry categories relates solely to condition of female ovaries.

Maturation stage (Hay, 1985)	Industry Stage	Roe yield approx. %	Comment on maturity
IV - Maturing	3-2	0-5	Gonads prominent. Extend full length of body cavity. Ovaries reddish orange to yellow; eggs distinguishable, opaque, variable in size, and separable. Testes mostly grey and will ooze sperm when sliced. Blood vessels clearly visible in the ovaries and testis walls.
V - Mature	2-1	7-10	Gonads bulging. No blood vessels visible in walls. Ovaries gold-yellow; eggs transparent and uniform in size. Eggs can be exuded under pressure and are adhesive. Testes milk-white; milt will flow under pressure.
VI - Running	1	10+	Gonads running. Eggs transparent. Eggs and sperm flow easily without external pressure. Just a few days prior to spawning.

SHOAL STRUCTURE AND DISTRIBUTION

Statistical comparison of biometric parameters measured for each shoal (Table 2.6) revealed that herring shoals recorded in the SoG were significantly larger in terms of biomass ($t=4.43$, $df=131$, $P<0.001$), had lower relative density (Mann-Whitney U test, z adjusted, $P=0.002$), more vertically extended ($t=4.27$, $df=236$, $P<0.001$) and positioned deeper within the water column ($t=11.02$, $df=309$, $P<0.001$). All t-tests were performed as one tailed with unequal variances.

Difference in average shoal biomass between areas is explained further on examination of the distribution of biomass amongst different sized shoals (Fig 2.17). The Central Coast is characterised by the predominance of very small, small and medium sized shoals which account for *c.* 80% of the total recorded biomass. Locations of the main concentration of shoals in the CC are shown in Fig. 2.18. Whilst small and medium sized shoals are similarly very abundant in the SoG, the situation is typified by the occurrence of several huge shoals which hold the majority of the biomass. Moreover, these huge shoals were found consistently at distinct locations throughout the survey period. Distribution centres of major concentrations of herring shoals in SoG (Fig. 2.19) are for the most part specific locations of individual huge shoals. Within these specific locations, shoals displayed restricted movements, typically only 1.5-3.5 km per day, this being associated with the tidal flow. In contrast, shoals in the CC were more transient in their nature, rarely being found consistently at specific locations.

Table 2.6 Statistical summary for 8 biometric parameters of herring shoals. Sample sizes (n) are given since due to operational limitations not all measurements were taken for every shoal in the SoG survey. Cl. Coeff. = mean NND/ mean \overline{ISD} .

	Biomass (t)	Bottom depth (m)	Relative depth (%)	Relative height (%)	Rel. density (1-5 scale)	Mean NND (km)	Mean \overline{ISD} (km)	Cl. Coeff
Strait of Georgia								
Mean	1461	62.05	65.2	37.4	4.18	0.65	45.6	0.014
Median	91	51	66.6	31.9	4	0.37	36.2	0.007
S.E.	311	2.80	1.7	2.0	0.11	0.10	1.8	0.002
n	132	162	162	162	111	105	105	105
Central Coast								
Mean	81	79.2	42.5	27.8	4.57	0.38	48.6	0.008
Median	45	72.7	37.5	20.0	4	0.19	43.8	0.004
S.E.	5.9	1.8	1.1	1.0	0.04	0.0	1.0	0.001
n	555	555	555	555	555	298	298	298

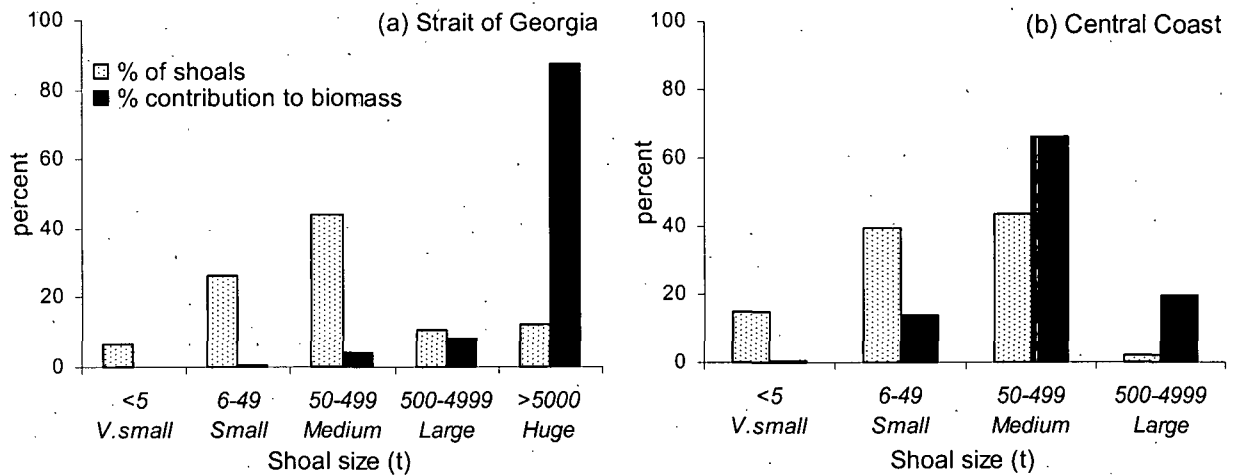


Figure 2.17 Distribution of shoal frequency and biomass in 5 size categories.

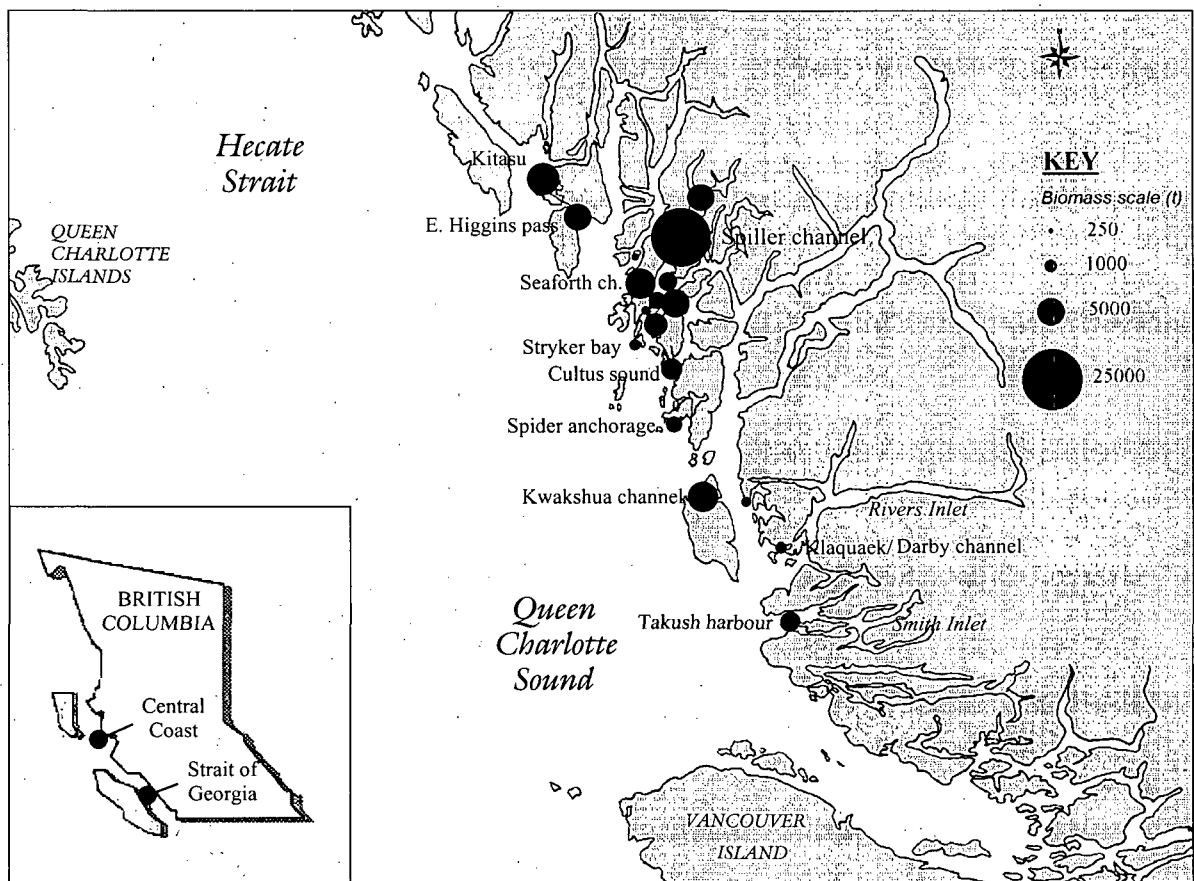


Figure 2.18 Distribution of major concentrations of herring shoals in the Central Coast (2nd -28th March 1998).

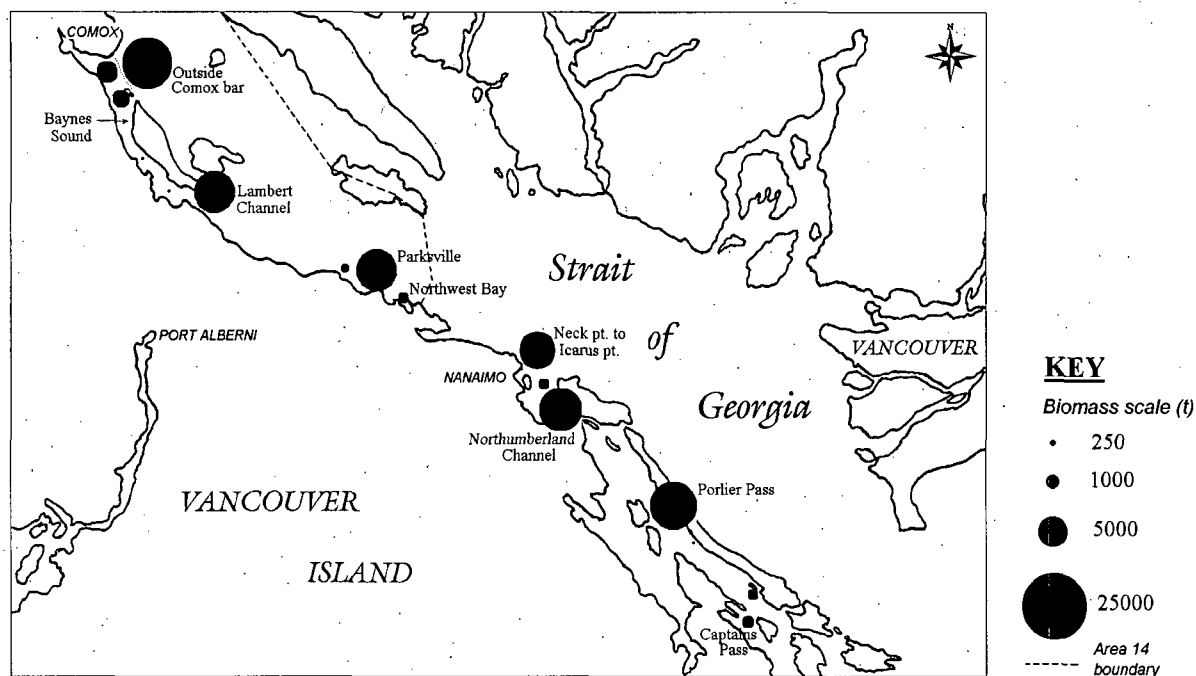


Figure 2.19 Distribution of major concentrations of herring shoals in the Strait of Georgia (27th February to 9th March 1997).

The higher relative extension of shoals in the SoG is a reflection of the observed differences in shoal shape (Fig 2.20). Streak shaped shoals, vertically extended through the water column predominated in the SoG particularly during the later stages of maturation. Strong associations with dips in the seabed were noted for bottom amorphous, found only in the SoG (Fig 2.21). The conspicuous absence of these streak-shapes of shoals, together with the high occurrence of spherical shoals associated with rises/drop-offs of rocky outcroppings in the CC (Fig. 2.22) (92% of the 236 shoals were found associated with specific features), points toward a connection between substratum type/topography and shoal shape.

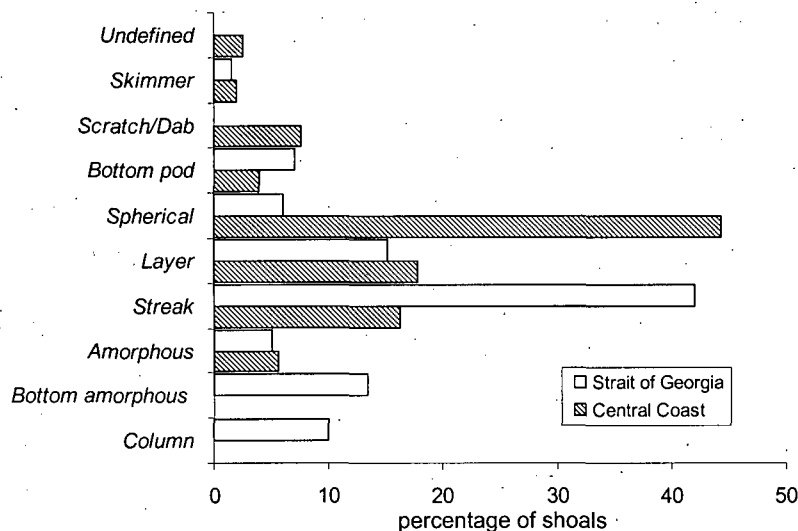


Figure 2.20 Occurrence of shoal shapes. SoG, n=108; CC, n= 555.

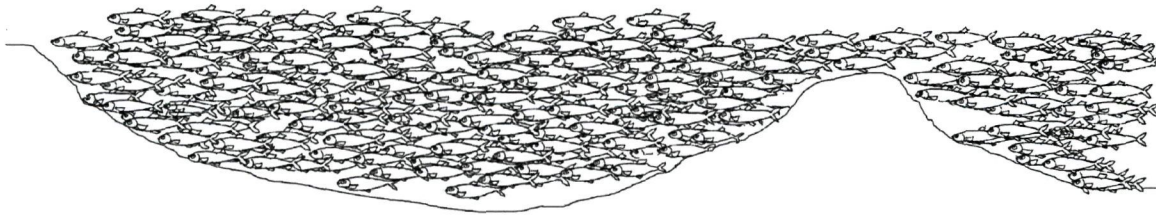


Figure 2.21 Association of herring shoals in SoG with dips in seabed (representation of acoustic trace).

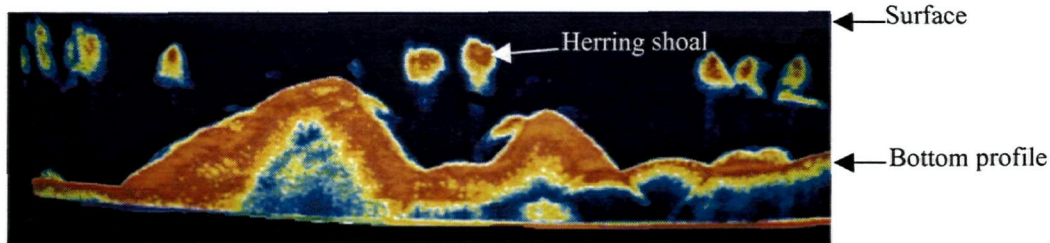


Figure 2.22 Echosounder recording of daytime small-medium sized, pelagic, spherical shaped shoals associated with rises/drop-offs of rocky outcroppings in Central Coast. Trace covers 2.3km.

Mean distance between nearest neighbouring shoals in the CC (0.38km) was almost half that of the SoG (0.65km) (one tailed t-test with unequal variances; $t = 2.41$, $df=147$, $P=0.008$), yet there was no significant difference in the average distance among all shoals (mean \overline{ISD}) between the surveyed areas (Table 2.6). This result implies that shoals of herring in the CC were found in tighter clusters than those of the SoG, and is supported by the significant difference in the cluster coefficient (mean NND / mean \overline{ISD} , see Mackinson et al. 1999 for details) (significance test, one tailed t-test with unequal variances; $t=2.65$, $df=137$, $P=0.004$).

Since larger shoals are the most important to commercial seine fishermen, analyses were performed to determine how very small, small, medium, large and huge shoals were distributed. χ^2 analysis showed that, in both regions, the frequencies of occurrence of nearest neighbour shoals for different size groups were not as expected by chance (SoG: $\chi^2=26.9$, $df=4$, $P<0.001$, CC: $\chi^2=152.9$, $df=9$, $P<0.001$) (Table 2.7). Moreover, the same pattern of distribution among different sized shoals was observed in the SoG and CC. Notably, very small, small and medium shoals had nearest neighbours of similar size more often than expected but did not occur as neighbours with shoals of a different size group as frequently as expected. Plots of shoal size versus size of neighbouring shoal (Fig 2.23) further emphasise this by the clustering of points in the centre, but also highlights the considerable range in size of neighbouring shoals. Regression analysis revealed a positive relation between size of adjacent shoals. However, only 4% of the variation in the relationship could be explained for the CC (ANOVA, $r=0.20$, $F=12.66$, $P<0.001$). The relationship is stronger for the SoG data (ANOVA, $r=0.81$, $F=141.94$, $P<0.001$) but is heavily biased by large and huge shoals occurring as neighbours on 3 occasions.

Table 2.7 Observed and expected (values in brackets) occurrence of different sized neighbour shoals in the CC. Chi-squared test is pooled for SoG due to low number of large and huge shoals occurring as neighbours.

		Shoal size group		
Strait of Georgia				
	<i>Small</i>	<i>Medium</i>	<i>Large+ Huge</i>	
<i>Small</i>	18 (11)			
<i>Medium</i>	20 (31)	29 (22)		
<i>Large+Huge</i>	4 (7)	6 (9)	4 (1)	
Central Coast				
	<i>V. small</i>	<i>Small</i>	<i>Medium</i>	<i>Large</i>
<i>V.small</i>	31 (7)			
<i>Small</i>	20 (35)	67 (46)		
<i>Medium</i>	8 (39)	80 (102)	81(57)	
<i>Large</i>	0 (2)	1 (4)	10 (5)	0 (1)

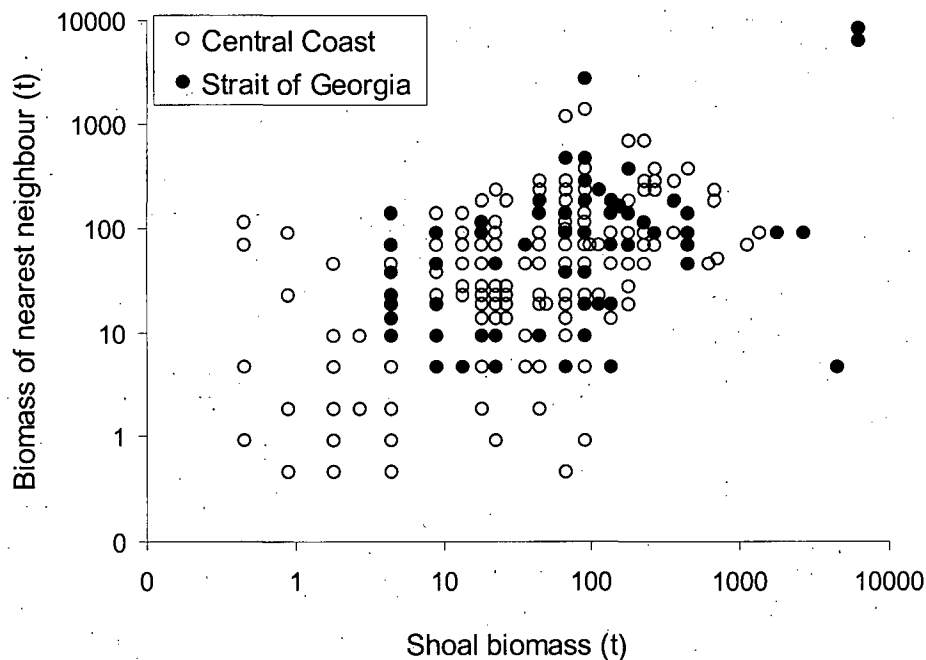


Figure 2.23 Size of adjacent shoals recorded on cruise track SoG and CC.

DIURNAL CHANGES

Diurnal changes in structure and distribution of shoals were observed in both regions. Dawn and dusk periods are included in the data, dark and light being classified between the times of sunrise and sunset. During dark periods, shoals typically occupied shallower water and were located higher in the water column. Although packing density was significantly lower during darkness, there was no apparent change in shoal size (Table 2.8). Shoals in the CC were found shallower in the water column than those in the SoG, during both day and night. Furthermore, the diurnal change in depth distribution was less marked in the CC than in the SoG, shoals being found distributed more evenly through the water column during the day than night (Fig. 2.24). Diurnal change in relative height is accounted for by changes in shape, shoals typically forming more flattened, layers during darkness. In the CC, shoals recorded during darkness were still inclined to associate with seabed features to a similar degree as that observed in the day.

To remove differences due to spatial variation, examination of changes in nearest neighbour and mean inter-shoal distance was confined to one specific location, in the Central Coast. Unfortunately the number of shoals detected was insufficient to warrant detailed analysis, although data recorded over different days, indicated that distance between neighbouring shoals was lowest during dusk and night, yet shoals were less clustered in their distribution than during the daytime.

Table 2.8. Summary table of diurnal changes in structure and distribution of shoals. t-test on mean values for 5 biometric shoal parameters. All tests, one tailed. (a) t-test with unequal variance. (b) Mann-Whitney U test, z adjusted.

	Biomass (t)	Bottom depth (m)	Rel. depth (%)	Rel. height (%)	Rel. density
Strait of Georgia					
Light	1408	68.4	71.9	36.5	4.4
Dark	1548	55.5	56.1	37.5	3.9
t-stat	0.22	2.32	4.67	0.25	1.99
df	130	146	140	162	100
P	not sig (a).	<0.01	<0.001	not sig (a).	0.05 (b)
Central Coast					
Light	84	87.4	45.7	24.9	4.7
Dark	85	64.1	32.2	30.8	4.2
t-stat	0.067	6.32	5.92	2.45	4.38
Df	483	326	328	194	483
P	not sig (a)	<0.001	<0.001	<0.01	0.001 (b)

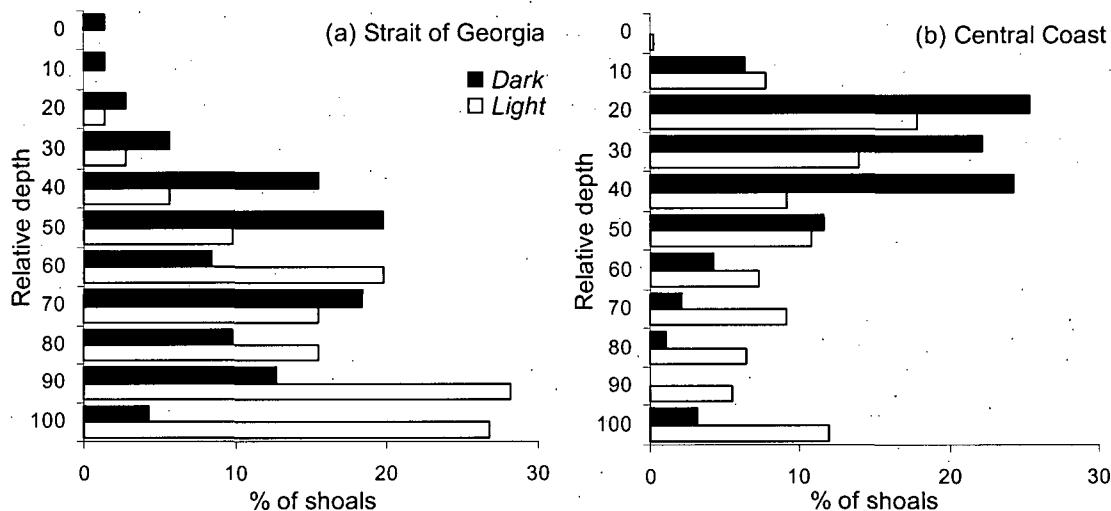


Figure 2.24 Diurnal differences in relative depth of shoals, (a) Strait of Georgia, (b) Central Coast.

TEMPORAL CHANGES IN RELATION TO MATURATION

Temporal changes in shoal structure and distribution are examined in relation to changes in maturation stage, inferred from catch data from roe-herring survey seine fishing vessels (Fig. 2.25). Each sample consisted of 100 fish from each seine set. Sixty three sets were made in SoG and 46 in CC.

Within shoals, no consistent temporal change was observed in fish size distribution. Length-frequency distributions were predominantly uni-modal (Fig 2.26); the mean size difference from lower to upper quartile ranges from all sets was 2.16cm (standard deviation = 0.42cm) (Fig 2.27). Most evident differences in size distribution occurred between specific locations within each region. For the CC, examination of test sets made in 5 specific locations, revealed herring from East Higgins pass to be significantly smaller (10 sets; 18.76cm) than those in Spiller channel (16 sets; 19.50cm) (one-tailed t-test with unequal variance, $t\text{-stat}=3.47$, $df=21$, $P=0.001$). Sex ratio's displayed variation between samples but were close to 1 for both regions (female:male ratio; SoG, 1.007:1, $n=9447$; CC, 1.04:1, $n=7631$), and no obvious temporal change could be detected. However, it is interesting that all 8 samples collected during 4th -8th March 1998 in CC contained c. 5-10% more males. It is not clear whether this marks a real difference in the sex composition of shoals during this period, or occurred somehow from biased sampling.

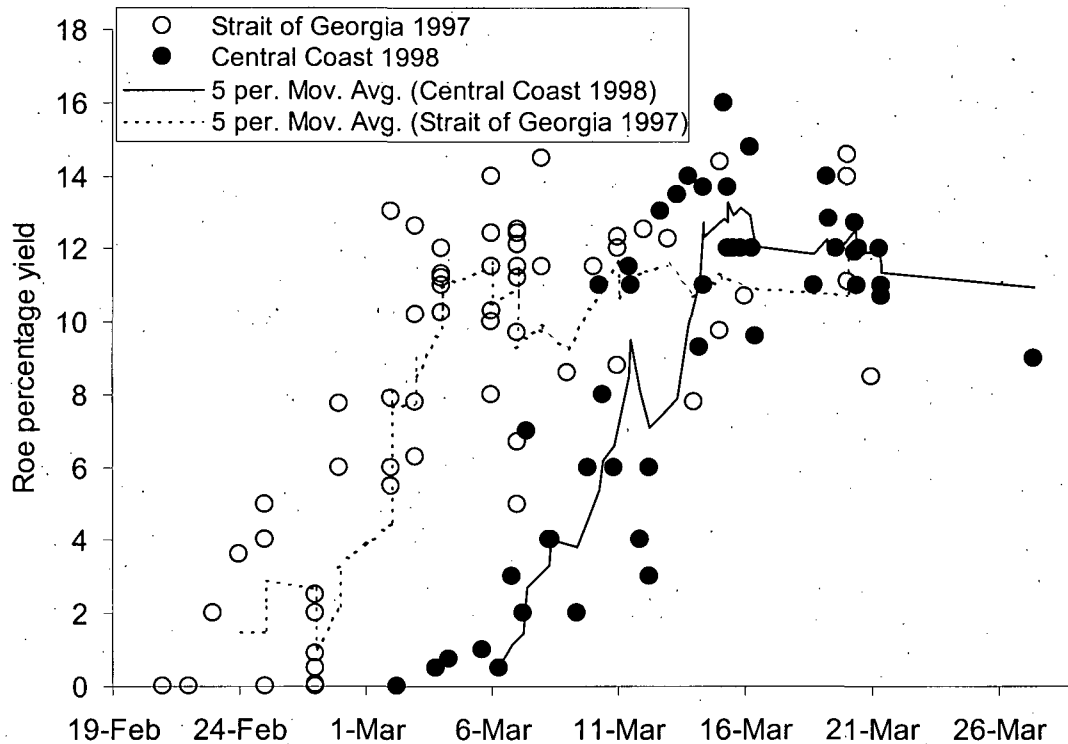
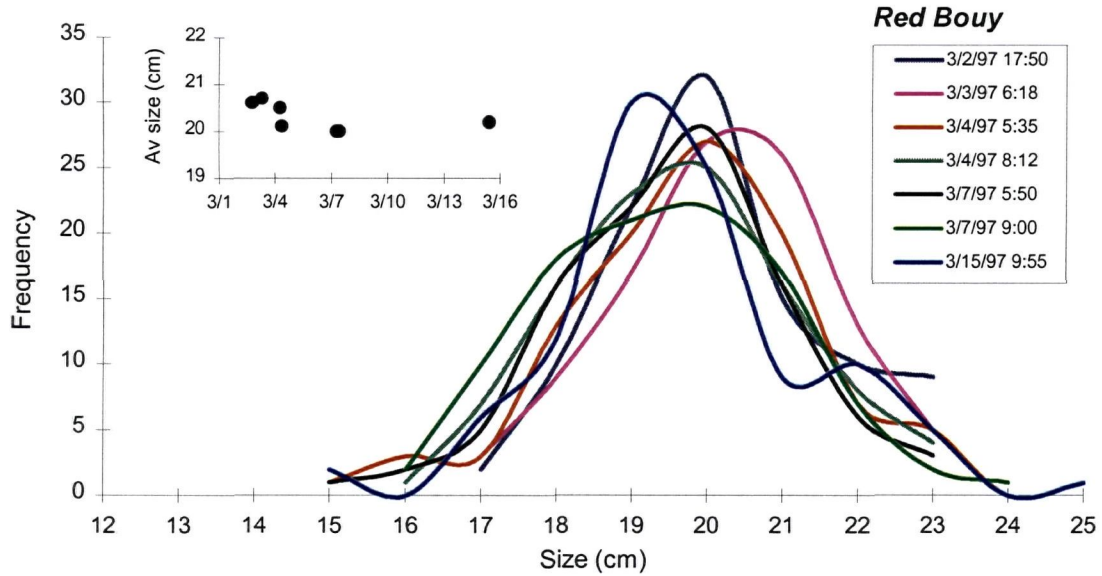


Figure 2.25 Temporal changes in maturation (% roe yield from females) in SoG (1997) and CC (1998). Differences in timing are primarily related latitude, herring spawning earlier in the SoG than those in the CC (Hay, 1985). Moving average plotted every 5 points to emphasise trend.

A.



B.

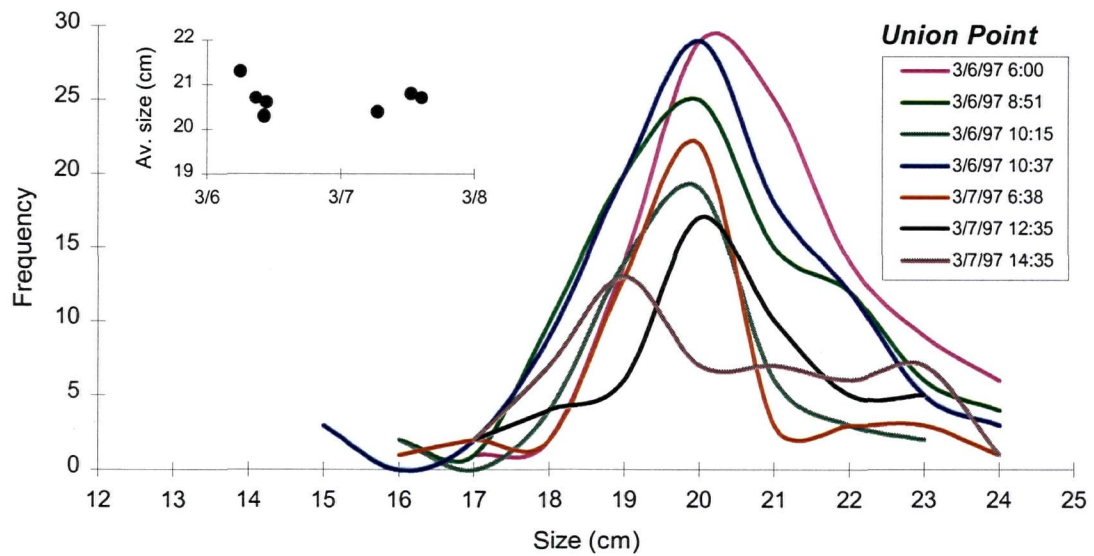


Figure 2.26 Frequency distributions of herring samples taken on dates through test sample period. Inset graph shows changes in average size for the same period. A. Red Bouy, B. Union point in SoG.

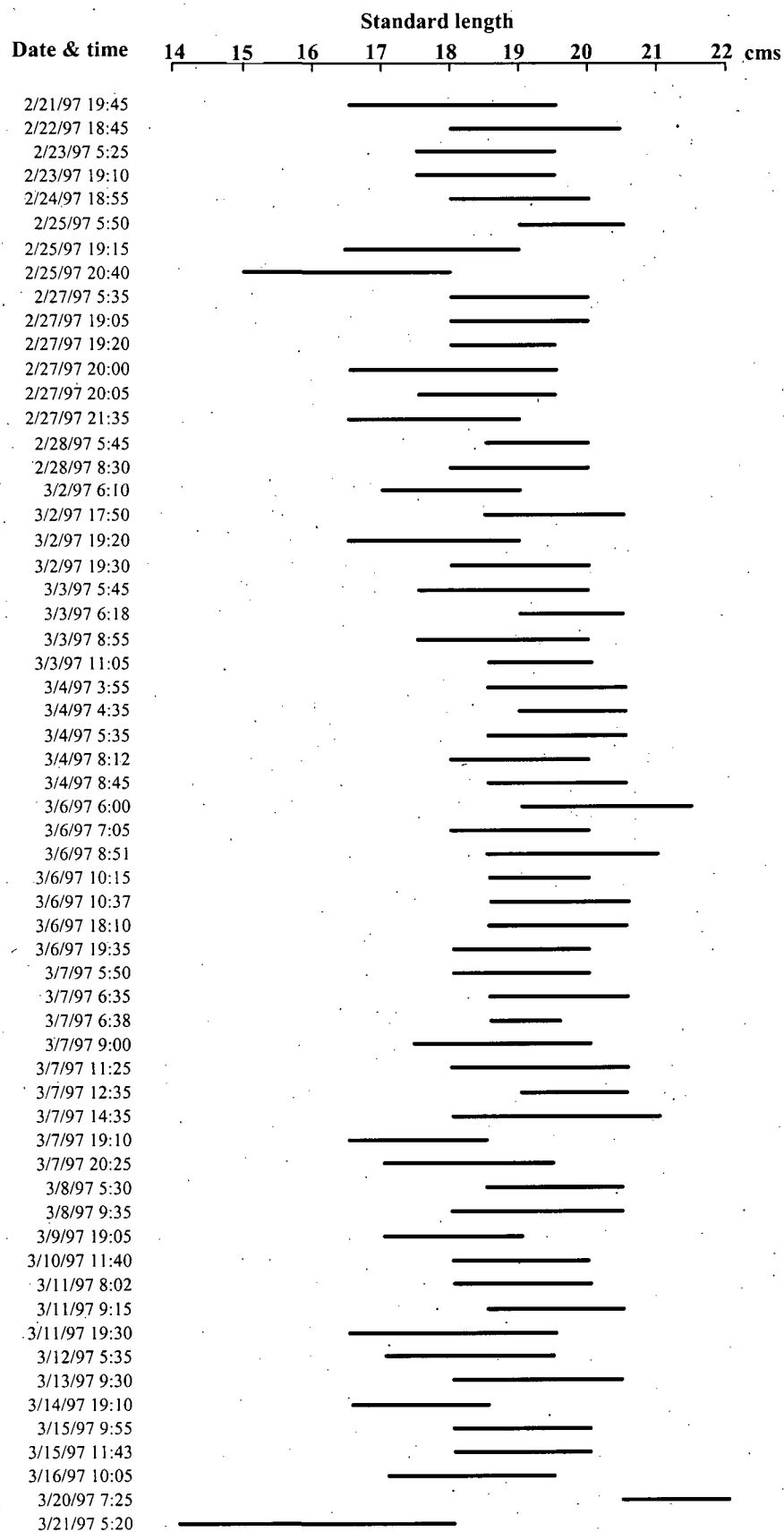


Figure 2.27 Lower and upper quartiles of size range from test samples in SoG.

To reduce the effects of spatial differences, a single locality from each region was selected for analysis of temporal changes in shoal structure and distribution; Baynes sound (Fig 2.28) in the SoG during 3rd to 8th March 1997, Spiller channel in CC during 7th-15th March 1998. Correlation coefficients for each biometric parameter vs. time (during the period of maturation shown in Fig. 2.25) were calculated (Table 2.9).

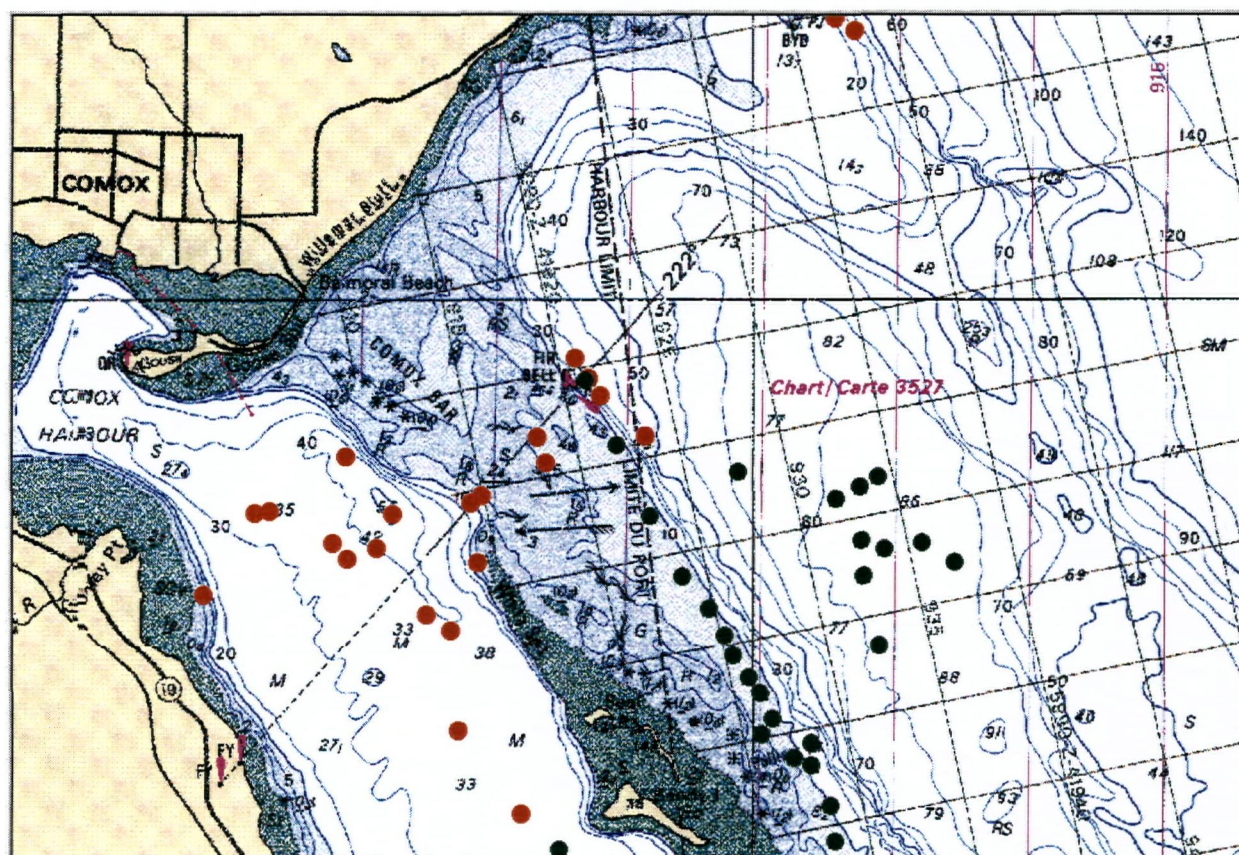


Figure 2.28 Distribution of herring shoals in Baynes sound (SoG) on 3rd March 1997. Red dots (lighter ones) are those recorded during the day and green dots are those recorded in the evening.

Table 2.9 Regression analysis results of changes in biometric shoal parameters over time. Significance test on the correlation coefficient at the 5% level.

	Biomass (t)	Bottom depth (m)	Relative depth (%)	Relative height (%)	Relative density scale
Strait of Georgia					
Corrln. Coeff.	-0.07	-0.09	0.12	0.23	0.21
Residual df	99	125	113	124	50
F	0.47	1.07	1.77	7.12	2.18
P-value	0.496	0.303	0.187	0.009	0.145
Central Coast					
Corrln. Coeff.	0.11	-0.19	-0.16	0.1	0.3
Residual df	209	209	209	209	209
F	2.46	7.94	5.3	2.07	20.34
P-value	0.118	0.005	0.022	0.151	<0.001

In Baynes Sound, SoG, relative height of shoals increased during the period of maturation observed. This corresponded, with an increased prevalence of streak shaped shoals. Biomass, relative depth and density of shoals did not show any statistically significant temporal correlation. In contrast, packing density of shoals recorded in Spiller Channel, CC, increased as maturation progressed and shoals occurred in shallower water. Furthermore, determination of the top 3 most frequently observed shoal shapes for each day during the period indicated that spherical shoals were more prevalent during later stages of maturation.

Examination of changes in mean NND and mean \overline{ISD} of shoals in Spiller Channel does not show any obvious change of spatial pattern in relation to maturation (Fig. 2.29). However, an interesting observation worth noting, is that during a storm on 8th March, neighbour distance between shoals increased and their distribution became more dispersed, as indicated by the elevated cluster coefficient value.

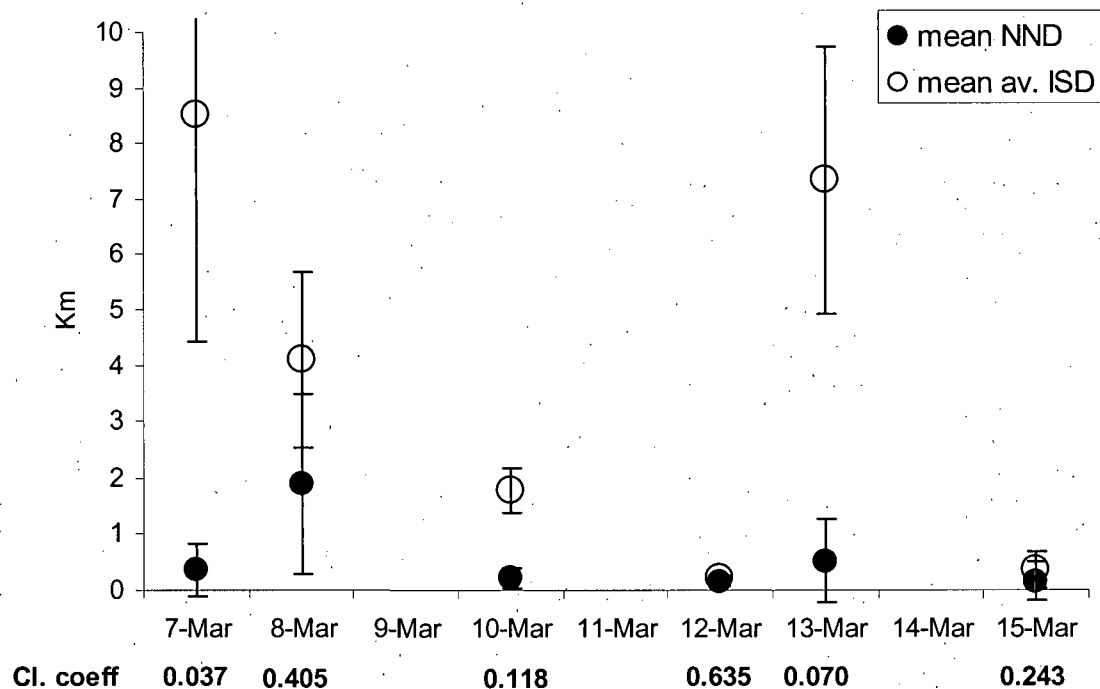


Figure 2.29 Changes in distribution pattern of shoals in Spiller Channel during maturation. Mean av. ISD is the same as mean \overline{ISD} (the mean of the average distance among all shoals).

OBSERVATIONS ON PREDATORS AND FEEDING

Birds were the most numerous predators visible in both regions. Larger birds (gulls and cormorants) appeared to concentrate primarily on the large aggregations of herring, their presence and distribution clearly demarcating the extent and shape of shoals. Smaller diving

birds (murre) were observed in association with most shoals. In the SoG, birds, sealions and seals were the only predators observed. Sealions and seals were an order of magnitude more abundant than in the CC and generally focused their attention on very large holding shoals, frequently hunting in packs of 50 or more. In the CC, sealions and seals occurred occasionally and fish predators including hake *Merluccius productus* and rockfish *Sebastes* sp. occurred in several test sets. In addition, porpoises and killer whales were observed displaying feeding activity in the presence of large herring shoals.

Six random samples of 25 fish from seine test sets made in SoG, indicated very limited and opportunistic feeding by herring. Predominant food items were eggs, scales and krill.

DISCUSSION

Acoustic surveys of pre-spawning Pacific herring revealed variations in the spatial and temporal pattern of shoals between regions. Whilst variation between years can blur regional differences in spatial structure, changes in maturation stage are probably responsible for similarities while behavioural adaptation to local external influences may explain the variation.

Despite considerable difference in the distribution of shoal biomass, small and medium sized shoals were most numerous in both regions and occurred as neighbours more often than with shoals of other size groups. A cautionary note is necessary concerning the interpretation of the distribution of shoal sizes; very small shoals may be under-represented in comparison to larger shoals due to their lower likelihood of detection in the acoustic field and the directed nature of the cruise track (DFO surveys focussing attention on large biomass areas). Within shoals, catch statistics revealed that herring of a similar size swim together, confirming experimental results (Pitcher et al. 1985). The variation in length of individuals was approximately 30%, as noted by Breder (1976).

During later stages of maturation (stage 2 to 1), huge shoals started to disperse and the occurrence of smaller, faster moving, more dense, streak shaped pelagic shoals, increased. These observations are supported further by the knowledge of experienced fishers and fishery managers regarding changes during maturation (Wilson pers. comm, McEachen pers. comm, Gordon pers. comm)⁴. A similar high occurrence of vertically extended shoals has been reported in Norwegian spring spawning herring in shoals found 4-5 days prior to spawning (Axelsen, 1997; Slotte, 1998), and are thought to be shoals immigrating and searching for suitable spawning habitat (Nøttestad et al. 1996, pers. comm). In the SoG, these smaller, vertically extended shoals are said by fishery managers to be 'on the move' (McEachen pers. comm) and have more dynamic characteristics in common with the spherical shoals observed in the CC.

⁴ Personal communications taken from notes made during formal interviews with fishers and fishery managers as part of ongoing research in to the behaviour and distribution of herring.

The regularity of observed shapes may be the consequence of individuals assuming a certain geometric packing structure that influences the external shape (Misund et al. 1995) yet, the function of streak shaped shoals observed here is not clear. Axelsen et al. (1998) suggested that vertically elongated shoals occur when individuals of different maturation stage have specific position preferences. Abrahams and Colgan (1985) argued that shoals of shiner (*Notropis heterodon*) in an aquarium, that became deeper vertically and more compact when attacked by large-mouth bass (*Micropterus salmoides*) did so to obtain an unobstructed view of the predator. However, it is difficult to accept that the same explanation would suffice for the size of shoals considered here. Since large shoals in shallow water are highly visible from above perhaps a streak shape reduces detection by avian predators? Spheroid or discoid shaped schools, like those observed in the CC are thought to minimise detection by searching piscine predators by providing the smallest visible area (Breder, 1976; Pitcher and Partridge, 1979).

Throughout the observed period of maturation, shoals in both regions exhibited a typical, 'Type-I' diurnal pattern (Neilson and Perry, 1990), the same as previously reported for Pacific herring (Thorne, 1977; Burton, 1990; McCarter et al. 1994). Fish within shoals spread out and rose toward the surface after sunset, and at dawn, coalesced again and dived towards the bottom. Furthermore, shoals displayed a significant tendency to move toward shallower water during darkness, the same pattern observed in menhaden (*Brevotia patronus*) by Kremmerer (1980). Avoiding predation is presupposed as the function of diurnal changes in behaviour. Indeed, nocturnal predators consume vision oriented fish more intensively in the dark the greater their concentration (Radakov, 1961 in Radakov, 1973). Thus, when fish cannot see well enough to perform co-ordinated defence tactics, dispersion at night is adaptive precisely for avoiding predation. Moving to shallow water close to the shore may provide benefits of structural refuge from predators.

Although herring in both regions exhibited the same diurnal pattern, daytime shoals in the CC were distributed relatively evenly through the water column in comparison to the deeper shoals in the SoG. The difference in behaviour is assumed to be linked to possible alternative anti-predator strategies associated with differences in the movement habits of shoals between regions, detailed discussion of which is provided below.

Three factors are proposed to explain the variation in structure and distribution of shoals between regions. Differences in behavioural adaptations to oceanographic conditions, predation risk and seabed substrate/topography can explain in part the observations that (i) shoals in the SoG were on average considerably larger, showed restricted movement, found relatively deeper in the water column and were vertically extended in shape during later stages of maturation; (ii) shoals in CC, were smaller, denser, typically spherical in shape, more transient in nature and more highly clustered.

The Strait of Georgia was typified by the occurrence of huge herring shoals (5,000 - 30,000t) 'holding' at specific locations during the early stages of maturation. These shoals share several similarities with overwintering shoals of Pacific herring (McCarter *et al.* 1994) being relatively non-mobile, mostly of uniform density and shaped as a layer. The ecological function of this is considered to conserve energy and minimise predation risk (Huse and Ona, 1996), during this non-feeding period. Moreover, 'holding' sites are generally located in deep water areas between island passes, and are characterised by high flushing; a feature that is presumed a necessity to very large non-mobile shoals requiring significant water exchange for adequate oxygenation of the many gills. This view is supported by MacFarland and Moss (1967, in Breder, 1967), who reported oxygen depletion in large schools of *Mugil cephalus* L. and suggested that oxygen depletion and associated decline in pH and increased carbon dioxide may be a factor in limiting school size based on respiratory need. For large shoals, selection of 'holding' areas typified by high water exchange could mitigate such effects.

An alternative view is that these specific locations represent areas where food is most likely to be found, even though it is recognised that during this period feeding activity is considerably reduced (Crawford 1980; Messieh *et al.* 1979; Parsons and Hodder, 1975; Nøttestad *et al.* 1996; Axelsen, 1997). Data collected here confirm that what little feeding activity may occur is opportunistic. The local distribution of pre-spawning North Sea herring is thought to be determined both by hydrodynamic process as well as the related occurrence of prey aggregations (Maravelias and Reid, 1997).

The non-mobile 'holding' shoals observed in the SoG are subject to heavy predation by sealions and birds. More important than conserving energy is survival, and perhaps this function is best served by forming very large shoals. Large shoals and shoal clustering decreases predation risk to individuals by lowering probability of detection (Major, 1978; Morgan and Colgan 1987), providing early discovery of predators (Magurran, 1990; Magurran *et al.* 1985), reduced risk of capture (Major, 1978), increased confusion (Landeau and Terborgh, 1986) and more effective evasion (Pitcher and Wyche, 1983). Field observations of Norwegian spring spawning herring suggest that larger shoals exhibit a greater repertoire of anti-predator tactics than smaller schools (Nøttestad and Axelsen, 1999). Large shoals also provide good opportunities for rapid reformation after predatory encounters, which may be particularly important when sealions utilise pack hunting strategies to separate groups of herring.

Many daytime shoals in the SoG formed strong association with dips in the seabed, a feature typical of the soft substrate that predominates in this region. Such strong habitat selection serves to lower predation risk (Lima and Dill, 1990; Magnhagen, 1993) by reducing exposed surface area, and further conserves energy through hydrodynamic advantage.

Herring in the CC do not generally display the same tendency for 'holding' as those in the SoG, and the impression gained during the survey was of a relatively more dynamic situation where

shoals formed temporary labile structures, moving in smaller schools (*sensu* Pitcher, 1983) and occasionally 're-grouping' in larger shoals at a different location, before splitting and dispersing again. Higher packing density of shoals observed in the CC is a result of their schooling habit, individual fish swimming more closely to maintain synchrony during travel (Pitcher and Partridge, 1979; Partridge et al. 1980). Close proximity to others may also allow individuals to monitor better the behaviour of neighbours that may alert them of approaching predators (Magurran and Higham, 1983), thereby reducing predation risk. Presumably, for small travelling schools, the anti-predator benefits of large size are outweighed by the ability to perform rapid, co-ordinated manoeuvres to evade predators. Breder (1976) provides comments in support of this hypothesis, noting that sharp turns of short radius are commonly made by small shoals up to sizes that are too large to act as a cohesive unit. In large dense schools, individuals are locked in and do not have the freedom of movement, thus they have problems turning, the presence of other fish bodies restricting them.

The rocky substrate and irregular topography characteristic of the CC may explain difference in distribution of shoals compared with the SoG. More than half of the shoals recorded were found in strongly associated with rises/drop-offs of rock outcroppings. Such tight aggregation around these features is assumed to be responsible for the more highly clustered distribution of shoals. By shoaling in the lee side of such features, presumably herring gain considerable hydrodynamic advantage. Maravelias et al. (1996) suggested that seabed substrate/topography was similarly responsible for determining the distribution pattern of North Sea herring.

To summarise: the maturation state of individual herring provides the motivation, direction and guidance to carry out their objective to spawn, but expected consistent temporal pattern is masked by high local spatial variation. Behavioural adaptation to external influences, including predation risk, differences in oceanographic conditions and seabed substrate/topography can help explain variation in structure and distribution of shoals in two contrasting regions of British Columbia.

Chapter 3

Information on herring behaviour, shoal structure, dynamics and distribution

3.1 Introduction

An overview of the two main sources of information about herring shoals in the literature is presented below. *Field studies* provide quantitative description of structure, dynamics and distribution of shoals of herring and other schooling fish in the wild. Due to the inherent variability of environmental (biotic and abiotic) conditions, it is difficult for wild studies to demonstrate conclusively how specific factors interact in a way that might produce observed patterns. As a consequence, confirmation and support is frequently sought from experimental and theoretical work. The quantitative empirical data gleaned from these sources is used in CLUPEX to define low-medium-high values for each shoal descriptor, used during the process of defuzzification, whereby discrete output values are derived from fuzzy conclusions.

Experimental behavioural studies focus specifically on identifying factors influencing behaviour of herring and other schooling fish under controlled conditions in fish tanks or confined arena. Although physical limitations imposed by the tank or arena forego the ability to examine aspects of shoal distribution pattern, experimental behaviour studies have been front and centre in advancing our understanding of the factors influencing the structure of fish shoals. Many studies are driven by a desire to understand the adaptive value of shoaling and schooling. The controlled environment has allowed researchers to tease out some of the fundamental behavioural decision making processes that are assumed to occur on a continual basis in the wild. The studies offer quantitative information on shoal structure and qualitative understanding of behavioural rules.

The extent of the treatment given in literature, to each factor influencing herring shoals is presumed to reflect their relative importance in determining shoal structure and distribution. This key assumption is used to mimic a hierarchy of importance of each attribute in the model by applying varying degrees of confidence to rules (see Chapter 5).

A complete functional breakdown of the information obtained from literature sources is provided in the *Questions and Answers* and *View Original Data Forms* tabs in the **Select Options** menu of the Knowledge-base.

- Under the *Questions and Answers* tab, you will find specific details of factors affecting shoal structure, dynamics and distribution. Supporting comments from each literature source are provided together with the bibliographic reference and an ID# which can be used to view the full reference and abstract (note that the reference ID# is different from the database record number).

- Under the *View Original Data Forms* tab, quantitative details of each shoal descriptor are summarised in 'Structure and Distribution Quantitative Data', and literature references are provided in full in 'References'.

Table 3.1a summarises knowledge on the relationships between attributes (factors affecting shoals) and descriptors (descriptive features of shoal structure, dynamics and distribution), gleaned from literature and interviews. The inter-relationships between shoal descriptors, for example how shoal shape and packing density change with swimming speed, are summarised in Table 3.1b. A categorisation of subjects discussed by each paper is given in Table 3.2; the frequencies are used in determination of the confidence applied to rules in the model (this aspect is discussed in detail in section 5.2, Chapter 5).

Table 3.2 Categorisation of shoal descriptors discussed in literature.

Descriptor		no. times discussed
Structure	Size	52
	Packing density	41
	Relative extent/area	20
	Shape	31
	Shoal cohesion	13
	Fish size comp.	12
	Fish direction	4
	Size segregation	14
Dynamics	Dynamic tendency	10
	Ease of capture	10
	Internal dynamics	14
	Swim speed	25
	Shoal move	4
Distribution	NND	5
	Clustering	13
	Shoal depth	42
	Shore distance	6
	Stock range fulfilment	6
	Feature association	16
	Location shift	3
Stock parameters	Age structure of stock	15
	Relative stock size	11
	Distribution limits	3
	Catchability (q)	10
Others	Avoid	13
	Predator attack rate	7
	Filter feeding	2
	Coastal features	1

Table 3.1a Summary table of relationships between attributes and descriptors used in CLUPEX. Numbers in each box are reference numbers to records in the knowledge-base (see 'Rule-Base' under the *View Original Data Forms* tab of the **Select Options** menu). Numbers in Brackets (X,Y): X - no. of interview records noting relationship. Y - no. of literature sources noting relationship.

Descriptors	Structure							Dynamics					Distribution						
Attributes	Shoal size	Pack dens	Shape	Cohes	Size comp	Fish dir	Size seg	Dyn tend	Catch ease	Int dyn	Swim speed	Shoal move	NND	mean ISD	Shoal depth	Shore dist	Stock range	Feat assoc	Loc shift
External - biotic	✓	✓	✓	✓				✓		✓	✓		✓		✓				✓
Aquatic predator abundance	43 (5,16)	36 (7,8)	34 (3,8)	112 (0,7)				33 (4,2)		35 (2,2)	4 (2,0)		31 (3,0)		32 (7,1)				39 (3,2)
Bird predator type					✓ 38 (2,2)														
Bird predator distribution		✓ 37 (2,1)																	
Competition	✓ 99 (2,1)	✓ 95 (1,0)	✓ 100 (0,1)					✓ 97 (1,0)		✓ 94 (1,0)	✓ 96 (1,0)								
Feeding mode								✓ 26 (1,0)			✓ 22 (2,0)								
Food abundance	✓ 15 (3,3)	✓ 21 (4,5)		✓ 111 (0,1)									✓ 28 (4,5)						
Feeding status	✓ 16 (4,0)	✓ 13 (6,2)						✓ 25 (2,3)		✓ 24 (3,0)		✓ 23 (2,0)							
Food depth distribution															✓ 27 (3,1)				
Food patch association																		✓ 30 (3,0)	
Food patch distance														✓ 29 (5,4)					
External - abiotic											✓		✓		✓				
Vessel avoidance											118 (0,2)		117 (2,1)		84 (6,7)				
Current depth															✓ 67 (1,4)				
Current direction						✓ 66													

						(1,0)													
Current strength			✓ 64 (1,1)															✓ 71 (3,0)	
Moonlight		✓ 7 (7,2)						✓ 115 (6,1)						✓ 8 (3,2)					
Oceanographic features																		✓ 107 (1,3)	
Spawning habitat availability	✓ 63 (1,1)																		
Temperature																	✓ 83 (4,1)		
Tide state														✓ 68 (7,1)					
Time of day/light		✓ 6 (13,6)	✓ 105 (1,1)				✓ 10 (4,1 3)	✓ 3 (0,1)	✓ 4 (2,5)	✓ 1 (1,2)	5 (2,0)	✓ 108 (1,1)	✓ 109 (1,2)	✓ 106 (1,4)	✓ 2 (18,4)	✓ 9 (12,6)			
Topography and substrate																		✓ 70 (16,5)	
Water depth							✓ 54 (1,0)								✓ 87 (2,3)				
Weather conditions												✓ 89 (5,1)		✓ 88 (6,1)					
Internal - biological	✓ 62 (11,4)	✓ 55 (8,5)	✓ 58 (8,5)	✓ 49 (5,3)			✓ 59 (4,4)	✓ 50 (7,5)	✓ 53 (4,1)	✓ 57 (2,2)	✓ 61 (6,2)	✓ 60 (4,1)	✓ 48 (4,2)	✓ 56 (8,0)	✓ 51 (12,5)	✓ 11 (8,0)		✓ 116 (0,1)	
Maturation stage																			
Stock age structure																	✓ 86 (3,3) + 92 (3,2)		

Descriptors - parameters characterising structure, dynamics and distribution of shoals. **Attributes** - factors influencing herring shoal structure, dynamics and distribution. **Abbreviations:** Pack dens - packing density; Cohes - shoal cohesion; Size comp - size composition of fish in shoal; Fish dir - shoal direction with respect to current; Dyn tend - dynamic tendency; Catch ease - ease of capturing a shoal; Int dyn - internal dynamics (schooling or shoaling); Swim speed - mean swimming speed of shoal; NND - mean nearest neighbour distance; mean ISD - mean of the average inter-school distance (distance from one shoal to all other shoals in location); Shore dist - relative distance to shoreline; Stock range - fulfilment of potential stock range; Feat assoc - association with physical/ oceanographic features; Loc shift - likelihood of being displaced from feeding location.

Table 3.1b Descriptor and attribute inter-relations used in the model.

	Shoal size	Packing density	Shape	Cohesion	Fish direction	Size segregation	Internal dynamics	Mean swimming speed	Catchability (q)	Stock area/range	NND	Mean ISD	Feature association	Feeding mode ¹
Shoal movements	✓ 73 (3,2)				✓ 69 (2,1)	✓ 75 (1,2)							✓ 77 (3,1)	
Relative stock size	✓ 93 (6,2)								✓ 103 (0,11)	✓ 92 (3,2)	✓ 114 (0,1)	✓ 91 (2,0)		
Fish length		✓ 76 (1,2)						✓ 74 (2,4)						
Mean swimming speed		✓ 81 (1,1)	✓ 79 (1,3)		✓ 65 (1,0)		✓ 78 (1,1)							
Shoal size		✓ 104 (0,1)		✓ 110 (0,1)										
Shoal depth			✓ 85 (1,1)											
Extent/Area		✓ 42 (2,0) + 14 (3,0) + 98 (2,0) + 12 (2,1)						✓ 80 (1,0)	✓ 102 (0,6)					
Shore distance	✓ 101 (1,0)													
Food size/abundance ¹														✓ 17 (1,2)

¹ - attribute inter-relation

3.2 Field studies on herring

In the past 10-15 years sonar and echosounders have been widely used for abundance estimation of schooling pelagic fish, and it is these studies that provide the majority of quantitative data on herring shoals. In particular, investigations into the impact of fish behaviour on the acoustic estimation of abundance (e.g. Gerlotto and Fréon 1988; Fréon et al. 1992; Fréon et al. 1993; Soria et al. 1996; Misund et al. 1996a, Misund, 1997) have yielded many useful observations on behaviour patterns of herring and other schooling fish.

Norwegian researchers have been at the forefront of many acoustic investigations on both Norwegian spring spawning herring and North sea herring, particularly during migrating/ocean feeding phases. Atlantic Canada has relatively recently focused attention on the use of acoustics for assessment of its Atlantic herring stocks (Anon, 1988; Wheeler, 1990; Stephenson et al. 1990). Surveys around Nova Scotia have been ongoing for some time (Shotton and Randall, 1982; Buerkle, 1985, 1987, 1989, 1990) and since 1989 acoustic surveys have formed the basis of scientific advice (Stephenson et al. 1990). A number of observations on schooling and distribution arise from such studies.

There are few specific studies of behaviour or schooling dynamics of Pacific herring to compare with those on the Atlantic herring. On the west coast of Canada, research on the spatial distribution of herring schools has been centred around studies of spawning stocks. There is considerable information pertaining to the distribution of spawning sites and how these have changed over time (e.g. Hay and Kronlund, 1987; Hay and McCarter, 1998). Acoustic surveys have been run in the past in British Columbia for the purpose of determining the feasibility of obtaining abundance estimates and determining the distribution of Pacific herring, but assessment surveys were discontinued in 1994. Currently the only use of acoustic surveys specifically for herring is in conjunction with in-season management for the sac-roë fishery. For each fishing area, chartered commercial fishing vessels are used to locate herring shoals and visually estimate their biomass (Armstrong, 1986). Chapter 2 section 2.2, provides the first detailed spatial analysis of this survey data. In other areas of the Pacific, notably Washington state and Alaska, there is greater emphasis on the use of acoustic techniques for stock assessment and several observations on herring school dynamics and distribution arise as a result. During 1971-1982, over 700 hydroacoustic surveys were conducted in south-east Alaska and Washington (Thorne, 1977; Mathison et al. 1983). Surveys were primarily done at night and comments on behaviour generally go only so far as to note typical diurnal variation in depth distribution.

Numerous acoustic studies have investigated behaviour and distribution patterns of other small schooling pelagic species, most notably *Sardinella* sp. Information from these studies is included in the expert system in support of observations on herring.

My review reveals that field studies contribute considerable information on eleven attributes that effect shoal structure, dynamics and distribution; (i) predators, (ii) food, (iii) light, (iv) vessel disturbance, (v) oceanographic conditions/ physical features, (vi) maturation, (vii) currents and water depth, (viii) weather, (ix) inter-specific interactions, (x) stock size and age structure, (xi) seasonal changes in motivational state. In the following review, for convenience, attributes are classified according to four categories; internal motivational, internal biological, external abiotic, external abiotic.

INTERNAL MOTIVATIONAL

Seasonal changes in motivation

Changes in the relative influence of attributes determining spatial distribution and organisation of shoals depend in part on seasonal alterations in motivational state of individual fish. Early observations on the reaction of herring to mid-water trawl (Mohr, 1971), showed changes in the behaviour of stocks occurred in relation to season and physiological state.

Diffuse widespread shoals are usually associated with passive phases in the life cycle and most pronounced during over-wintering in deep water. Overwintering Norwegian spring spawning herring (Huse and Ona, 1996) and Pacific herring display the same behaviour (Thorne, 1977; Keiser et al. 1987; McCarter et al. 1991, 1994). Herring feed little (Parsons and Hodder, 1975) and typically occur in one very large shoal. Substantial loss of body fat, and dormant state of gonads suggests that little somatic energy is used for gonad development, indicating that this is a stage of energy saving. The overwintering period appears largely to be an exercise of energy conservation and predator avoidance (Winters, 1977). In Norwegian fjords the main predators are cod, saithe, and killer whales. In addition to schooling by day, the herring prefer to be at depth to avoid surface oriented killer whales. Energy expenditure is mainly related to swimming activity and it seems that specific strategies are adopted to conserve energy (Huse and Ona, 1996). Potential energy saving derived from lower respiratory rates of fish in larger groups (that occur as a consequence of reduced timidity and nervousness Itazawa et al. 1978 - in Pitcher and Parrish, 1993) may in part explain the very large shoal size characteristic of the overwintering period.

During pre-spawning and spawning period, herring are observed mostly in concentrated aggregations, often in contact with the sea floor (Mohr, 1971). Predator avoidance and reproduction are assumed to be dominant motivation factors, since herring feed only opportunistically (Mackinson, Chapter 2, section 2.2), stored lipids supporting gameto-genesis (Slotte, 1999).

Immediately after spawning, spent fish occur in small groups and scattered schools. Hunger is the primary motivation, herring feeding voraciously as they migrate back to offshore feeding grounds (Hourston and Haegle, 1980; Nøttestad et al. 1996). During the migration to feeding grounds schools are typically ovoid in shape, keeping their shape both day and night, travelling at a continuous speed (Mohr, 1971).

Spring spawning herring continue to feed through summer to late autumn increasing their oil content and condition factor (Ware, 1985), before migrating back to coastal overwintering areas. Throughout the summer, dominant motivational factors may change continually depending on the balance of hunger and threat of predation. Comparative observations suggest that summer shoals are smaller and considerably more mobile than winter shoals (Buerkle and Stephenson, 1990).

INTERNAL BIOLOGICAL

Maturation

During pre-spawning maturation, changes in shoal structure and distribution characteristics may occur on a daily basis. Detailed acoustic observations describing the changes in swimming speed, density, size, shape, depth and distribution have been made on Norwegian spring spawning herring (Nøttestad et al. 1996; Axelsen et al. 1998) and Pacific herring (Mackinson, Chapter 2 section 2.2). Both species display similar behaviour, the main difference appears to be in the spawning act itself; although there are a few exceptions, Atlantic herring spawn in deeper water on stones and gravel, whilst Pacific herring spawn in shallow inter-tidal zones on aquatic vegetation.

During early stages of maturation both Atlantic and Pacific herring commonly congregate at specific locations in very large shoals (>5000t), deep in the water column and display strong association with particular physical features (Slotte, 1998; Mackinson, chapter 2, section 2.2). At this time they are typically more skittish than those found during later stages (Mohr, 1971). As maturation progresses to the 'substrate searching phase' (Nøttestad et al. 1996), large shoals segregate in to smaller, more densely packed, mobile shoals of varying size (Wood, 1930; Mackinson Chapter 2, section 2.2) that are frequently vertically extended in shape (Mohr, 1971; Axelsen, 1998; Slotte, 1998; Mackinson, Chapter 2, section 2.2).

Mature fish close to spawning become more sluggish and may not show the regular diurnal vertical migration or same strength of reaction to vessels observed in earlier stages (Wood, 1930; Mohr, 1971). Indeed, a degree of habituation seems to occur; fishermen talk about allowing the fish time to "harden" (become less skittish) and will delay fishing to wait for this (Schwarz and Greer, 1984). Similarly, it is the experience of capelin (*Mallotus villosus*) fishers that during

spawning migration, capelin do not react much to noise from vessels (Misund et al. 1993). Prior to spawning, herring shoals may re-join to form larger spawning groups.

During spawning, herring associate intimately with the spawning substrate and may remain there from 1 to 7 days (Axelsen et al. 1998), presumably depending on weather conditions, tide and shoal size relative to the availability of suitable substrate. Frequently, 2-3 spawnings may occur at the same location, separated by 10-15 days (Hay, 1985; Ware and Tanasichuck, 1989) and the trend for large herring to spawn earlier is widespread among stocks (Wood, 1930; Hay, 1985; Slotte and Johannessen, 1996). The number and relative size of spawning waves might relate directly to the age structure of the reproductive population; spawning proceeding consecutively through year classes from oldest to youngest due to differential maturation (Lambert, 1987). Aneer et al. (1983) conducted detailed observations of spawning Baltic herring. During spawning they were generally found in shallow water following the extension of substrate belt.

Recovering spent herring look like sprinklings on an echosounder. These very small, loosely packed shoals are widely distributed and disperse rapidly, swimming fast and high in the water (Mohr, 1971; Haegeler and Schweigert, 1985; Nøttestad et al. 1996), as they begin offshore migration.

Stock size and age structure

Both relative stock size and age structure influence large scale distribution of herring shoals (e.g. Petitgas and Samb, 1998), which is in turn connected to abundance related changes in catchability (e.g. Winters and Wheeler, 1985). From a tagging study on Pacific herring, Hourston (1980) concluded that immature fish home to a lesser degree than adults and noted that the result suggested that homing contains an element of learning, being related more to previous spawning experience than to where the fish themselves were hatched. An important implication is that stocks whose age composition is severely truncated, may not have the same learning opportunities and thus cannot be expected to fulfil their potential range, even when stock size is high. Experiments of migration routes with French grunts (*Haemulon flavolineatum*) (Helfman and Schultz, 1984) demonstrated that control fish that had no opportunity to learn, showed no migration directionality and did not return, as did those with the opportunity to learn. The information necessary to maintain migration traditions is presumed to be transmitted socially via learning from other, usually older, individuals (Helfman and Schultz, 1984). Further supporting evidence is provided by the changes in distribution pattern of Norwegian spring spawning herring before and after stock collapse (Bergstad et al. 1991; Rottingen 1990, 1992; Slotte and Johannessen, 1996). Irrespective of the importance of learning, Sinclair et al. (1985) consider that "The dual characteristics of homing to natal spawning areas (Sinclair and Isles, 1985) and larval retention severely restrict the ability of a spawning population to re-populate continuously over-fished areas".

EXTERNAL BIOTIC

Predators

Herring were observed to dive from the surface to the bottom when killer whales entered a fjord. Since the herring dived when outside the killer whales' range it was assumed that they were probably responding to sound from the whales (Similä and Ugarte, 1993). In response to cooperative feeding by the killer whales, herring packed in to tight balls; a behaviour which serves to increase the success of the killer whales who direct their effort toward keeping the ball very dense and driving it close to the surface (Similä and Ugarte 1993). In the same location, Nøttestad and Axelsen (1999) observed that killer whales attacks on herring were made predominantly on small ($<540\text{m}^2$) dense and circular schools. Schools greater than 500m^2 were not attacked and were noted as displaying a broader anti-predator repertoire. Un-attacked schools had significantly lower density than attacked ones. Fréon et al. (1992) found the same results in simulated predator attacks (a towed tuna model) on *Harengula* schools. Tight schooling, or ball formation is known as a defence mechanism used by schooling fish, typical anti-predator tactics such as de-organisation and clumping (Pitcher et al. 1996) resulting in changes in local density.

Pitcher et al. (1996) recorded over 230 behavioural events, from tracked herring schools on the Norwegian shelf. At the rate of approximately once every 5-minutes, school structure changed in response to approaches by other herring schools, likely predators, and the research vessel. Interpretation of the visualisation of the schools by sonar suggested adaptive responses to different kinds of predatory attacks. Individual cod and haddock predators intimately accompanied the herring schools, their attacks causing frequent modification to, but not dispersal of, school structure. In contrast, rapid approach by fast moving schooling predators such as saithe, or by the research vessel, caused the herring to dive steeply. A similar study of behavioural dynamics, conducted in the Norwegian Sea revealed the number of behavioural events per hour was significantly higher during night than daytime, a result attributed to dynamics associated with feeding and avoiding predators. Furthermore, the observed tighter clustering of shoals at night allows herring to maintain a collective vigilance, decreasing predator pressure through the dilution and abatement effect (Pitcher and Parrish, 1993), whilst continuing to feed. (Mackinson et al. 1998; Chapter 2, section 2.1)

Pacific herring form a large part (30% by volume) in the summer diet of hake, and herring seem to shift their feeding location to regions which avoid significant overlap with hake (Tanasichuk et al. 1991). Prior to hake arriving, herring feed in the most profitable area; after their arrival, an apparent trade-off between feeding and avoiding being fed on, results in herring shifting location.

Food

During ocean feeding, distribution of herring shoals is intimately linked the abundance and horizontal and vertical distribution of food. Jakobsson (1961) found large shoals of herring to be positively correlated with the abundance of the copepod *Calanus*. Clusters of shoals occur at regions of high productivity (Maravelias and Reid, 1995; Fernö et al. 1998, Mackinson et al. 1998, Chapter 2 section 2.1). The complex hydrodynamic processes causing patchiness of prey distribution are of course related to, and to some extent determine the local distribution of herring (Maravelias and Haralabous, 1995).

Feeding fish have a tendency to spread out and are often horizontally flattened in shoal shape (Nøttestad et al. 1996; Mackinson et al. 1998, Chapter 2 section 2.1). Feeding activity also increases behavioural dynamics. Mackinson et al. (1998) recorded significantly more behavioural events during night-time feeding of Norwegian spring-spawning herring.

Inter-specific interactions

In multispecies clusters, different inter-specific interactions may account for observed changes in shoal structure and distribution. Massé et al. (1996) observed that in the case of a horse mackerel (*Trachurus* sp.) with anchovy (*Engraulis encrasicolus*) mix (pred-prey interaction), an upward displacement of anchovy was observed. In contrast, no vertical modification was noticed for a sprat (*Spratus spratus*)-anchovy mix (competitive interaction) but there was a distinct change in shoal shape, shoals tending to be more flattened.

EXTERNAL ABIOTIC

Light/ Time of day

Diurnal changes in light intensity have profound influence on the structure and vertical distribution of herring shoals. This phenomenon seems to occur during all seasons and has been described many times for both Atlantic and Pacific herring. A brief account follows. Daytime shoals swim deep in the water column, forming discrete, dense, variously shaped schools closely associated with features of the seabed (depth permitting) (Blaxter, 1985; Buerkle and Stephenson, 1990; Robinson et al. 1995; Petitgas and Levenez, 1996).

At dusk, shoals break their association with the seabed and rise in the water column (Butcher, 1985). Packing density is progressively reduced, and shoals comprised of a mixture of small and large fish may exhibit a vertical separation as a result of individual decisions to swim next to neighbours of similar size (Pitcher et al. 1985). Smaller fish swim at the top part of the shoal [Schafer, 1955; Breder, 1967; DFO, 1991; Brodeur and Wilson, 1996; (Sette, 1950; Breder 1951; Niquen 1986 - in Pitcher and Parrish, 1993)]. Average distance between nearest neighbour shoals

and between all shoals declines, resulting in an overall distribution that is still aggregated (shoal clusters occur) (Fréon et al. 1996) but less patchy overall (Thorne, 1977; Gerlotto and Petitgas, 1991; Mackinson et al. 1998, Chapter 2 section 2.1). As shoals rise higher in the water column, seine fishers enjoy increased success of capture (Tester, 1938; Misund, 1990; Misund, 1993b; Michalsen et al. 1996).

By night time, shoals are typically distributed in a low density layer in the upper quarter of the water column (Mathison et al. 1983; Burton, 1990; Mackinson Chapter 2, section 2.2). The area over which they are distributed is further reduced although the distribution pattern of shoal clusters may remain similar (Mackinson et al. 1998, Chapter 2, section 2.1). During the night, a horizontal component can accompany vertical migration (Thorne, 1977; Kremmerer, 1980; DFO, 1991; Gerlotto and Petitgas, 1991; Robinson et al. 1995) some herring (assumed to be the smaller ones (DFO, 1991)) moving towards the shore. In the dark of night, the diffuse layer of fish reduces the ease of capture (Mohr, 1971).

At dawn fish become increasingly active (Radakov, 1960) with the re-formation of schooling habit and re-assembly of distinct school clusters. The discrete more densely packed schools, still relatively high in the water column form an easy target for the seine fisher. This period of high contrast, like dusk, is also a period of high predation from piscine predators.

Effects of moonlight may modify the 'typical' diurnal pattern in two ways. During moon bright nights, herring generally rise faster in the water column at dusk and tend to spread out in lower density shoals extending over a wider area (DFO, 1991). However, by nighttime they are often distributed deeper in the water column than normal (Blaxter and Holliday, 1969). Catches of herring are known to vary with moon phase. Butcher (1985) comments that the October full moon was a good time for North Sea herring; the driftermen used to have good catches, presumably because the herring spread out a lot and thus were more likely to get caught in drifter gear. In contrast, Californian sardine fishermen, who rely on capture of whole schools by seining, tied up during full moon period because they caught so few fish (Clark, 1956 - in Blaxter and Holliday, 1969).

Oceanographic conditions/ physical features

GEOSPACE group (1993) consider the main factor affecting the vertical and horizontal distribution of shoals is that of hydrological discontinuities; "The densest aggregations are often observed close to the physical fronts: the limit of vertical light penetration, the thermocline and pycnocline, are at the same time attractive forces that concentrate prey, and an impassable frontier for some organisms. Horizontally, the frontal areas produce a similar effect. We may also include the dramatic changes in hydrological structures produced by storms, which induce an unstable distribution of the organisms".

Maravelias et al. (1996) show that although patches of herring extend over most of the North sea they tend to concentrate in an area 300 by 600 km and that clustering of shoals is likely linked to oceanographic features such as temperature and salinity fronts at a scale of 5-20 km. As a rule, herring concentrate in areas where food is associated with the presence of fronts and currents (Maravelias and Haralabous, 1996; Fernö et al. 1998).

Castillo et al. (1996) found a highly aggregated spatial distribution of anchovies (*Engraulis ringens*) and sardine (*Sardinops sagax*) that was influenced by the presence and intensity of coastal thermal and haline fronts. Differences in school types of *Sardinella aurita* (mainly) in Senegalese waters were found to be more related to geographic (i.e. hydrological) conditions than to seasonal effects (Gonzalez et al. 1998).

Pre-spawning herring positively associate with particular topographical features and substrate types, e.g. rocky spikes in areas of hard substrate and surface irregularities in areas of soft substrate (Reid 1995; Maravelias and Reid, 1995; Maravelias et al. 1997, (North Sea herring); Jakobsson, 1961; Slotte, 1998 (Norwegian spring spawning herring); DFO, 1991; Mackinson, Chapter 2, section 3 (Pacific herring). In particular, positioning of shoals in relation to physical features seems to confer hydrodynamic relief from tidal currents.

Currents and water depth

Water currents are known to influence the vertical distribution of fish; some fish avoiding increased current speed, others utilising them for transport either by passive or modulated drift (Michalsen et al. 1996). Schools of migrating Norwegian spring spawning herring are commonly found as deep as 500m, presumably using favourable currents to aid migration. Even during the night they may remain deep either to gain advantage from favourable currents, avoid predators and/or because feeding opportunities exist at such depths (Mackinson et al. 1998, Chapter 2 section 2.1). In other regions herring schools are generally found shallower than 200m, even when water depths are considerably deeper. Depth distribution of food and currents may play a critical role in determining shoal depth. Ocean feeding Pacific and North Sea herring (in open water) are found mainly at depths 100-150m (Hourston and Haegle, 1980; Maravelias et al. 1996).

In strong currents, shoals typically assume a hydrodynamically efficient shape. Bolster (1958) recorded cigar shaped herring shoals in strong tidal streams of the northern North Sea.

Weather

Bad weather tends to spread the distribution of herring shoals. Wood (1930) noted that catches of drifter boats during pre-spawning increase significantly during bad weather, presumably because the fish disperse. In contrast, when fish are aggregated in schools the driftermen generally had

poor catches. Keenlyside (1955) observed that on calm days, most shoals of rudd (*Scardinius erythrophthalmus*) oriented toward shore. On windy days, they stayed deeper in the water.

Vessel disturbance

Herring display an avoidance response to the sound of vessels that consists of a vertical and horizontal component. When in front of the vessel they dive, increasing swimming speed and then move away to the sides as the vessel approaches and passes over. Significant reductions in fish density most commonly occur at the moment of vessel passage (Mohr, 1971; Olsen et al. 1983; Soria et al. 1996). Misund et al. (1996b) noted that about 20% of herring shoals reacted to a research vessel, with avoidance being detected up to 1000m. Moreover, the reaction appears to be stronger during pre-spawning migration than when hibernating, feeding or on feeding migration (Mohr, 1971; Misund, 1990). Observations on the reaction of *Sardinella aurita* to vessels (Gerlotto and Fréon, 1992) show that although reaction is rather limited in comparison to herring, the responses are similar; (i) all schools dive before passage of the boat, (ii) the diving reaction is inversely proportional to initial depth of school, (iii) the upper layer of the schools become compressed as they dive.

Kremmerer (1980) presents evidence suggesting that fishing (or vessel avoidance in general) alters the structure and distribution of shoals. After no disturbance during the weekend, catches and shoal size of Menhaden (*Brevotia patronus*) was larger on Mondays and shoals were closer to the coast than later in the week.

3.3 Experimental behavioural studies

Experimental research has tended focus on examining how specific attributes change shoaling rules. The four main attributes studied are: (i) predators, (ii) food, (iii) light, (iv) sound. Several studies deal with the effects of multiple factors, examining the behavioural responses that result as a consequence of decision trade-offs between conflicting interests such as foraging and avoiding predation.

Predators

Shoals typically form schools (polarised, co-ordinated groups) in the presence of predators (Pitcher and Parish, 1993). After exposure to predation shoal size increases (Major, 1978; Pitcher et al. 1986b; Hager and Helfman, 1991; Krause and Godin, 1994; Krause et al. 1998a). Individuals gain considerable benefits from doing so since individual risk of predation decreases at a decelerating rate with increasing prey shoal size (Godin, 1986; Krause et al. 1998a). Larger schools benefit from increased vigilance and detection of predators (Godin et al. 1988); larger schools of minnows, detected an approaching model pike (*Esox lucius*) earlier than small schools (Magurran, 1990). Also, Morgan (1988) found that attacks by predators decreased as shoal size

increased. Moreover, increasing shoal size can decrease the success of the predators' attack per encounter with prey (Neill and Cullen, 1974), partly because attacks on larger shoals last longer, and fish become increasingly difficult to catch as a hunt goes on.

Schooling behaviour and inspection behaviour may actually inhibit attack by predators (Magurran, 1990). School clustering can decrease predator pressure through the dilution and abatement effect (Pitcher and Parrish, 1993).

In addition to forming larger shoals, increasing packing density is another anti-predator tactic (Keenlyside, 1955; Blaxter and Holliday, 1969; Major, 1978; Pitcher and Wyche, 1983). Increased packing density is a direct consequence of individuals increasing school cohesiveness (*sensu* Morgan, 1988) by reducing the frequency or duration of straggling from schools when predators are present (Andorfer, 1980; Partridge, 1982; Morgan, 1988; Krause and Godin, 1994). Simple, selfish avoidance of individuals to a predator can lead to aggregation and higher packing density within shoals as individuals try to get away from the periphery and locate themselves in central positions Hamilton (1971).

Spheroid (Breder, 1976) or discoid shaped schools (Partridge, 1978) are thought to minimise detection by searching piscine predators but, according to Pitcher and Partridge (1979), for schooling fish, the length in the direction of travel is usually the greatest dimension followed breadth and depth, typically in a ratio of about 3:2:1. During predation events, tightly packed balls of fish may serve to inhibit or deflect attack, as may the silvery wall caused by a closely packed schooling fish suddenly changing direction (Pitcher and Parrish, 1993). Abrahams and Colgan (1985) found that schooling shiners (*Notropis heterodon*) swim in the same horizontal plane in the absence of a predator, but stagger themselves into a more 3D arrangement in the presence of a predator; an arrangement that might offer a less obstructed view of the predator (Pitcher and Parrish, 1993).

Habitat shifting offers another strategy to avoid predation and is known to occur when the best areas for foraging are also the most dangerous and the forager must trade-off energy gain against predation risk. Stoneroller minnows (*Campostoma anomalum*) may shift in to shallow habitats in the presence of large-mouth bass (Lima and Dill, 1990).

Food

Although fish in larger shoals may gain benefits through sampling behaviour (Pitcher and Magurran, 1983), for hungry fish it is suggested that smaller, less cohesive schools are better for optimum foraging, a reduced overlap of perceptive field resulting in less competition and less interference of individual feeding acts (Blaxter, 1985). In support of this, Van Havre and Fitzgerald (1988, - in Lima and Dill, 1990) found that hungry sticklebacks are more likely to associate with small than large shoals. However, the reverse was true for satiated fish. When fish

are well fed and food is abundant, reduced competition and the desire to maintain anti-predator advantages of larger shoals may result in the joining of shoals. Although no quantitative estimate of shoal size was given, Jakobsson (1961, - in Blaxter and Holliday, 1969) found large shoals of herring to be positively correlated with the abundance of prey.

During food deprivation experiments a significant reduction in shoal density and time for fish to encounter food was noted when compared to the well fed condition (Morgan, 1988; Robinson and Pitcher, 1989b; Robinson, 1995); presumably hungry herring maintain a large distance from neighbours to improve feeding opportunities. Keenlyside (1955) similarly observed packing density is higher when fish are well fed than when starved. Increased activity (Robinson, 1995) and dispersion implies that starved fish are more likely to discover new food, whilst maintenance of shoaling ensures efficient consumption when food patches are discovered.

Different feeding modes may be employed to best capitalise on the patchy abundance and different sizes of prey. At low food concentrations, herring feed by selective capture of individual prey items. At high food concentrations, filter feeding offers a better strategy since the capture rate achievable by biting is constrained by the maximum rate at which they can bite, whilst filter feeding capture rate is directly proportional to prey concentration (Gibson and Ezzi, 1992). Blaxter (1985) showed that adult and juveniles can switch to a filter feeding if offered smaller (300-400 μ m) food particles.

It is no surprise that shoal distribution pattern is also strongly affected by food distribution. Lab studies have shown that in the absence of predators, fish congregate according to the profitability of food patches (Milinski, 1979; Godin and Keenlyside, 1984) or simply where food patches are found (Robinson et al. 1995). Diurnal vertical migrations may track that of prey species (Melle et al. 1994).

Several authors have examined how shoaling rules are modified when fish are forced to make trade-offs between foraging and avoiding predation. Experiments demonstrate clearly that prey animals measure risk when deciding whether to forage (Pitcher et al. 1976; Morgan and Colgan, 1987; Lima and Dill, 1990; Milinski, 1993). For example Morgan (1988) found that in Bluntnose minnows (*Pimaphales notatus*) the time delay in initiating feeding increased in the presence of a predator and decreased with both increasing shoals size and the degree of food deprivation.

Light

School structure changes markedly during vertical migration and is considered to be largely controlled by visual response to light intensity. Experimental treatment of this phenomenon is minimal in comparison to the wealth observations in the wild. Typically, adults spend daytime in schools near seabed and at dusk move up toward surface; light preference is 1 lux (Blaxter, 1985). As visual attraction ceases, fish disperse. At dawn, light intensity rises above the

threshold required for visibility between fish. Individuals re-form in compact schools and descend in the water column. Investigations by Radakov (1973) showed that nocturnal predators consume 'vision-oriented fish' (such as herring) in the dark more intensively the greater their concentration, thus it is believed that dispersal at night in vision-oriented fish is adaptive precisely for the reason of avoiding predation. In a review of diurnal vertical migrations in marine fishes, Neilson and Perry (1990) classify herring as having a typical type-I vertical migration (surface during night, bottom during day) whose parent rhythm seems to depend on light regime. However, it is recognised that there is considerably flexibility in this pattern that corresponds to seasonal changes in food distribution, local conditions and ontogenetic changes.

Sound

Avoidance in response to fishing vessels has been most widely studied during field surveys, the particular interest being how vessel avoidance affects acoustic estimates of abundance. In an experimental examination of behavioural responses of net penned Pacific herring to various taped-recorded sounds, Scharwz and Greer (1984) found that herring did not respond visibly to any of the taped sounds of natural origin (e.g. rain on the water, gull cries, killer whale vocalisations, barks of stellar sea lions and sounds made by herring themselves) or to sonar or echo sounders. In contrast, they typically produced an avoidance (feeding fish lessened the inter-fish distance, became more uniform and polarised, resulting in a fairly compact school moving away from the sound source), alarm or startle response to other sounds (e.g. moving and stationary (idling) vessels, deck gear and synthesised sounds). Soria et al. (1993) provide evidence that small pelagic fish can be stress conditioned. Most importantly they show that conditioned fish, when mixed with non-conditioned fish (naïve), can lead reactions in a school. The ability to learn from previous experience, or from other neighbouring individuals has adaptive advantage in many respects and many explain the poor response of herring to natural sounds observed by Schwarz and Greer (1984).

3.4 Summary

By influencing the behavioural responses of individual fish, two broad categories of factors determine the structure, dynamics and distribution of herring shoals. *External* factors are comprised of biotic attributes, such as food and predators, and abiotic attributes such as light, habitat and oceanographic features. *Internal* factors include hormone mediated changes in motivational state (Colgan, 1993) and inherent biological processes and constraints such as, maturation and swimming speed (He and Wardle, 1988). The key attributes (and most studied) are considered to be predation, food, reproductive state and light and this is reflected in the frequency in which these subjects are discussed in the literature. The dynamic interplay of all attributes insist that herring frequently re-appraise the balance of these, often conflicting, forces (Fernö et al., 1998). Consequent trade-offs result in alterations of shoal structure, dynamics and distribution.

Chapter 4

Local knowledge on herring

"When it comes to understanding fish behaviour and the many environmental factors that help determine and predict it, marine biologists must often take a back seat. This is hardly surprising. There are hundreds of times as many fishermen today than there are marine biologists, and there forebears were plying their trade and passing on their accumulated knowledge tens of centuries before anyone ever heard of marine biology. What is surprising is how little effort has been made by scientists to search out and record this information" Robert Johannes -from "Words of the Lagoon"

4.1 Introduction

Given our incomplete understanding of ecological mechanisms, attempting to predict the distribution and structure of herring shoals is an formidable task. Despite recent attempts to link cross scale behaviour dynamics and distribution studies (e.g. Mackinson et al. 1999b), there are still large gaps in our basic knowledge.

Since many herring fisheries are typically conducted at spatial scales of one to tens of kilometres and occur for periods of days to weeks, both fishers and fishery managers alike operate within the same meso-scale realm as the fish. By virtue of their profession, it is prerequisite that they have practical, applied knowledge regarding the distribution and behaviour of herring. Combining their observations with more conventional 'hard data' from scientific studies and theoretical interpretations provides a means by which we may bridge some gaps in our knowledge regarding herring behaviour and its influence on shoal structure and distribution (Figure 4.1).

There are many notable references on the importance of local/traditional non-scientific knowledge. Typically anthropologists have been in the forefront of these investigations, but an increasing number of ecologists are becoming involved. Johannes (1978) provides an enlightening account of the knowledge of Palauan fishers in Micronesia, demonstrating how it by far surpasses the current base of scientific understanding. Other examples include animal behaviour (Jones and Konner, 1989), and resource management (Dahl, 1989).

The knowledge from interviews is primarily qualitative and descriptive in nature and used in CLUPEX to define rules linking biological and environmental factors to changes in herring shoal structure, dynamics and distribution.

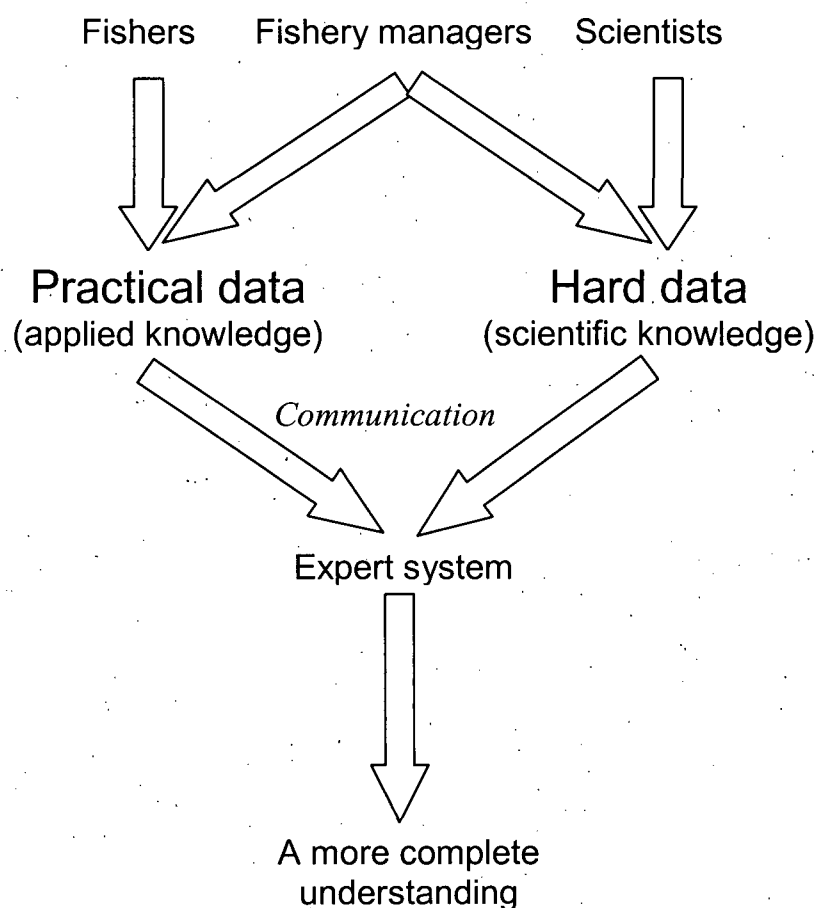


Figure 4.1 Combining sources of data (from Mackinson and Nøttestad, 1998).

Interview results are detailed extensively in the knowledge-base. In the **Select Options** menu, see the *Questions and Answers* and *View Original Data Forms* tabs. Under the *Questions and Answers* tab you will find specific details of factors affecting shoal structure, dynamics and distribution. Supporting comments from each interviewee source are provided together with its reference and ID# which can be used to view the interview transcript (found in the **Select Options** menu- *View Original Data Forms* tab - 'Interviewee Details').

An overview of findings is presented in Table 3.1, a cross-referenced summary of the ways in which attributes affect structure, dynamics and distribution of herring shoals.

4.2 Interview selection and technique

In this investigation, a total of 30 formal interviews were conducted, half with fishery scientists and fishery managers (8+7, respectively) and half with fishers and First Nations, (9+6, respectively), all of whom were previously or are currently herring fishers.

With the exception of one gillnet fisher, who specifically undertook herring surveys, all fishers interviewed were seine fishers from British Columbia, Canada. They had a collective experience (CE) of approximately 270 fishing years and provided professional practical local knowledge. Seinners were specifically chosen as candidates in contrast to gillnetters or roe-on-kelp fishers, since seine-fishing typically involves an element of search and thus requires specific knowledge of fish distribution and movements. The First Nations CE amounted to approximately 290 fishing years.

Selection of interviewees was deliberately non-random. An attempt was made to interview those fishers who had the most experience fishing herring during different seasons, at different locations, and who held respect of other fishers in the community. For this reason, progressive selection of interviewees was conducted by word of mouth, one candidate suggesting others to talk to. This method proved to be very successful. Fishery scientists and managers were selected based on their experience with herring. The current regional herring co-ordinator and 3 long time British Columbia fishery managers (CE approx. 160 years) offered a more technical 'field based' perspective that complimented observations by fishers. Three herring scientists from the Pacific Biological Station, Department of Fisheries and Oceans (CE approx. 75 years), and a further 5 from Norway (Institute of Marine Research and University of Bergen; CE approx. 80 years) provided hard scientific data from field and experimental studies.

Typical interview duration was 2 hours but ranged from 1- 4. With two exceptions, all interviews were conducted on a separate individual basis at the preferred location of the candidate. For help with interpretation, it was necessary on one occasion to interview two fishers together. In another instance, a meeting was held with the First Nations Sliammon band elders, that included men and women who had traditionally been involved in herring fishing prior to the demise of their local herring stock.

Interviewees were asked to: (1) recount what they had observed regarding distribution and behaviour of herring; (2) offer possible explanations to account for their observations. All candidates were asked the same type of questions although specific interviews were 'free range' or 'adaptive' in the sense that the format and directness in which the questions were presented depended upon the context of discussion (Hart, 1989). Allowing discussion to continue openly in this manner provided insight into many aspects which would have been overlooked by a simple questionnaire offering only a fixed set of responses. All interviewees were questioned on the same topics. On almost all occasions, new knowledge was acquired.

Using the same technique as Johannes (1978), the honesty and trustworthiness of the subjects' answers and was tested by asking two types of questions at a convenient time during discussion. The first were questions to which the answer was already well-known (e.g do herring feed during pre-spawning?). Responses to these questions were almost always the correct answer or that they didn't know. The second type of question sounded plausible, but were ones that the fishers were

unlikely to be able to answer (e.g. how do birds locate herring schools sitting on the bottom during the day?). In virtually every instance, the response to this type of question was "I don't know", indicating that individuals freely admitted their ignorance.

Interviews were recorded by hand written notes then subsequently typed and resent to the candidate within 48 hrs for verification of accuracy, corrections and additions. Prior to interviewing, candidates signed an informed consent form (University of British Columbia) affirming that the information received would remain their property and that reference would be given directly to them when cited. Details of all candidates together with a full transcript of their interviews is recorded in the knowledge-base (**Select Options** menu - *View Original Data Forms* tab - 'Interviewee Details'). In addition to interviews, 18 questionnaires were posted by e-mail to researchers involved with herring stock around the world. Despite a second reminder, there was only one response that contributed to the knowledge-base.

4.3 Responses

There was clear demarcation in the type of responses given by different interviewees. Typically, fishers were particularly strong on *observation* providing detailed accounts of school structure, distribution and behaviour including: school size, shape, density, depth distribution, association with specific features, ease of capture and specific behaviour patterns relating to season, tide, weather, fishing vessels, time of day, feeding and occurrence of predators. However, when asked 'why?'; they were generally reluctant or found it difficult to offer an *interpretation* for their observations. An attempt to elicit a rank order of factors they considered important in determining the observed shoal structure, distribution and behaviours was unsuccessful. It was seemingly an almost impossible task for many and was subsequently abandoned for an alternative approach.

In contrast, fishery scientists were more familiar and at ease with offering interpretations for their observations or experimental findings and for the most part, were able to assign an order of relative importance to the factors contributing to shoal structure, distribution and behaviour patterns.

Responses of fishery managers were more akin to those of fishers, being grounded firmly in field observation. However, due to the nature of their job, most were uncomfortable with ascribing behaviours to any particular factor. They tended to err on the side of caution and uncertainty, usually offering provisos and comments of exception to any of their observations. They were however, more willing than fishers to offer potential interpretations, and it was apparent that these were frequently guided by scientific understanding from colleague fishery scientists.

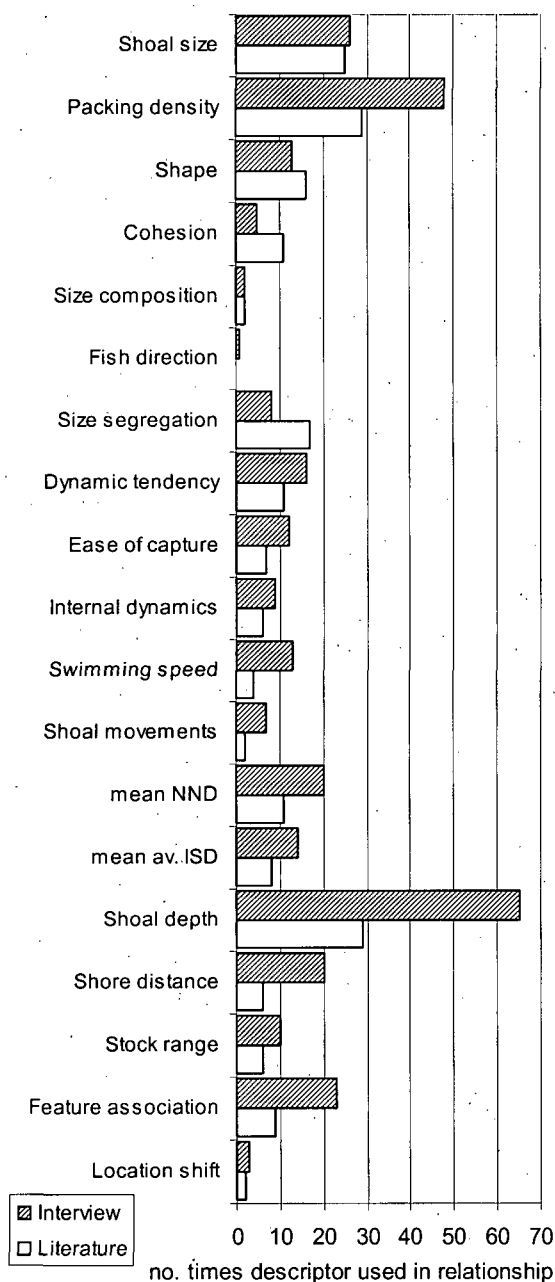
Remarkably there were no instances in which knowledge accumulated from any single source opposed another or diverged from that known from scientific studies. Information either complimented previous knowledge (from interviewees or literature) or added additional understanding.

Terms used to describe shoals were frequently different than those used in scientific literature and accordingly, some interpretation was necessary on my behalf. Despite this, with the exception of the descriptor, 'fish direction', interviews did not identify any additional descriptors of shoal structure, dynamics or distribution that were not previously identified from literature (Figure 4.2a). The point of departure from knowledge obtained in literature reflects the functional nature of the knowledge, particularly that of fishers. Numerically and proportionally more observations were directed to shoal features and factors influencing them, that are particularly relevant to the ability to locate and capture shoals. For example, interviewees yielded more comments regarding biophysical influences on shoals including time of day, moonlight, topography and substrate, and weather conditions (Figure 4.2b); and how these influenced descriptors such as shoals size, depth distribution, packing density, ease of capture, speed, dispersion (mean NND and mean \overline{ISD}), distance to shore, and association with features. It is noteworthy that the large number of comments on effects of maturation stage reveal the fact that most herring fishers in British Columbia have extensive knowledge of pre-spawning herring, the season during which the commercial fishery occurs. Table 3.1 provides a more specific categorisation of the relationships identified by interviews and literature.

4.4 Discussion

Despite potential biased perceptions of resource abundance and their impacts, knowledge of fishers can be a fountain of information (e.g Johannes, 1978). Frequently their knowledge is compiled over time based on that of their parents, grandparents and others with whom they have fished. The interviews in this study reveal that fishers closely observed physical environmental conditions and temporal changes resulting in variation in distribution, size and ease of capture of schools. However, in contrast to interviewed scientists and fishery managers, fewer were prepared to suggest behavioural interpretations for their observations. With the exception of several enthusiastic individuals, it did not appear 'necessary' that they should ask why? Neis et al. (1996) found a similar response from interviews with cod fishers; "...fishers' knowledge of fish stocks is primarily acquired to optimise catches while minimising effort. Therefore, they tend to closely observe those environmental features which are linked to fishing success: seasonal movements, habitat preferences, feeding behaviour and abundance dynamics; as well as those physical attributes that affect fish distribution, the performance of gear and fishing time: wind direction, currents, water temperature and clarity, bottom characteristics and local assemblage structures, as well as gear fouling".

(a) Descriptors



(b) Attributes

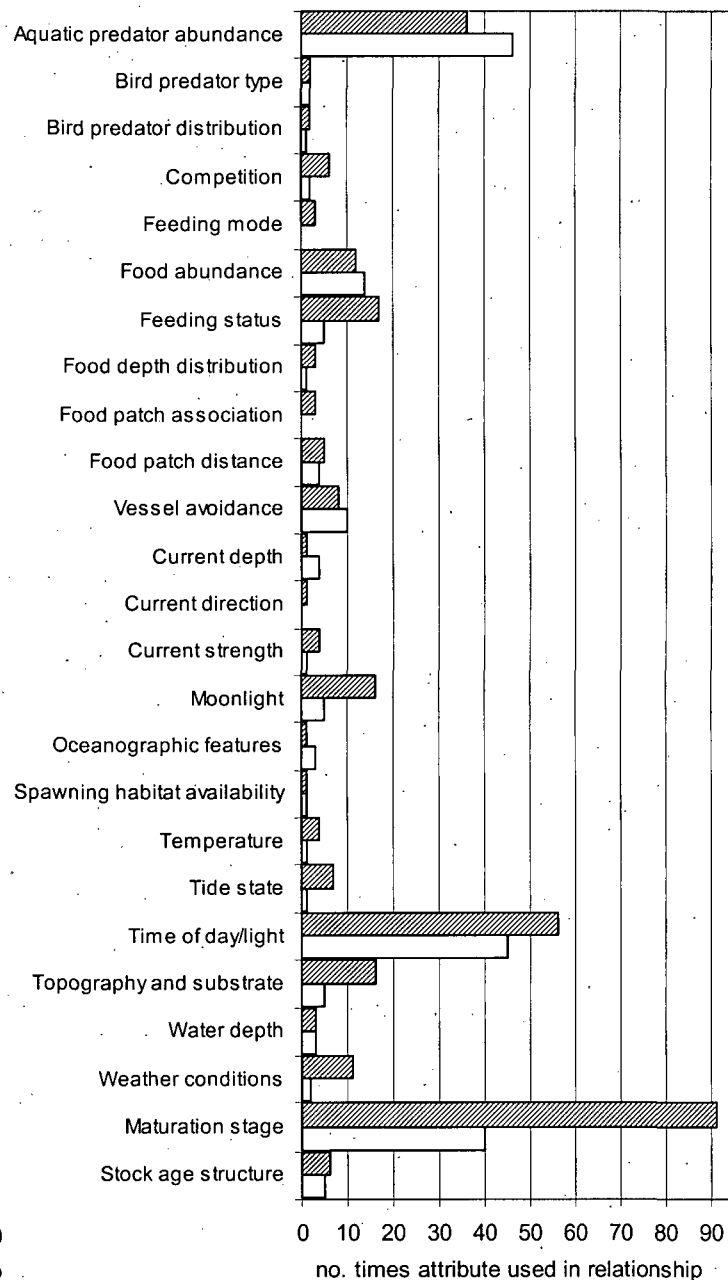


Figure 4.2 Comparison of descriptors and attributes derived from interviews and literature sources that were later used in forming rules. Abbreviations: mean NND - mean Nearest Neighbour Distance; mean av. ISD = mean \overline{ISD} (mean of the average Inter-shoal distance).

Remarkably, there was no conflict in the information obtained from fishers, scientists and literature sources that could not be explained by observations at different scales. More 'unique' instances of information were obtained occasionally from fishers. Information from scientists, fishery managers, field observations and literature accounts tended to support and compliment knowledge given by fishers rather extend it.

On consideration of the responses to specific questions used as test controls for assessing the trustworthiness of answers, it was deemed that all information relating to distribution and structure of shoals was accurate according to memory. Although on several occasion there were tendencies for 'stories', when asked a specific question, the response of interviewees was straightforward and no attempt was made to conceal ignorance of any subject. Where peculiar or unique observations were made, these were deliberately verified with other subjects in subsequent interviews. Further validation was conducted during the 1998 Pacific herring survey (Chapter 2 section 2.2), during which an attempt was made to verify interviewees observations. In support of the approach used here, Hutchings (1996) noted how improved communication with fishers can lead to testable hypotheses regarding the biology of northern cod.

Chapter 5

An Adaptive Fuzzy Expert System for Predicting Structure, Dynamics and Distribution of Herring Shoals (CLUPEX)⁴

5.1 Introduction

Much of our current understanding of fish distribution is qualitative and/or highly uncertain. Such information does not lend itself well to mathematical representation and consequently traditional numerical modelling may not be appropriate (Saila, 1996). Here, an alternative way of representing and applying knowledge is developed. A fuzzy logic (Zadeh, 1965, 1973) expert system is used to combine scientific information and knowledge of fishers to enhance our understanding of herring shoal structure, dynamics and distribution. Using input pertaining to the biotic and abiotic environmental conditions, the system, "CLUPEX", uses heuristic rules to predict structure, dynamics and meso-scale distribution of shoals of migratory adult herring during different stages of their annual life cycle. The predictions are generalised to 2 different herring species and thus may be used broadly to examine the impacts of shoal structure and distribution on management of herring fisheries.

5.2 Model development - methods and approach

Note: The software used to develop CLUPEX was Exsys[®] *Professional* by Multilogic (www.multilogic.com).

CLUPEX incorporates two fundamental sources of information on herring behaviour and distribution patterns; (i) 'practical' data: local knowledge from interviewed fishers, fishery managers and First Nations people (Chapter 4); (ii) 'hard' data: scientific information from; field work studies (Chapter 2), published literature sources (102 references that also include information on other shoaling fish, Chapter 3) and, interviewed fisheries scientists (Chapter 4). All knowledge contributes equally in building the knowledge-base. Therefore, an assumption is equality in the degree of belief in a piece of information from either fishers, fishery managers, fishery scientists, First Nations people or from literature. In this way, the potential of all data sources is maximised (Mackinson and Nøttestad, 1998). The information from all sources is recorded in the "knowledge-base" that is cross-referenced directly to rules in the model.

⁴ Parts of the work detailed in this chapter have formed the basis of a publication (Mackinson, 1999)

Forming functional relationships using rules

In essence, structuring of the heuristic model involves building a multi-layer decision tree. Heuristic rules written in natural language form relationships between *attributes* influencing herring and *descriptors* of shoals (Table 3.1). The majority of rules are taken directly from the information source whilst others are defined on best inference.

Rules have the form IF *a certain situation occurs* THEN *a known outcome is likely* and may contain several conditions in the IF part linked by AND, OR, NOT, and one or more elements in the THEN part linked by an AND. Since the goal is to conclude upon how behavioural responses to the influence of various combined factors produce changes in shoal structure, dynamics and distribution, *attributes* are typically used in the IF part of rules and *descriptors* in the THEN part. For example:

IF fish direction facing current
AND current strength *strong*
THEN mean swimming speed low (item confidence = x)
AND shoal shape horizontally elongated (item confidence = y)

Heuristic rules capture knowledge contained in linguistic expressions given by interviewees. By "computing with words" (L. Zadeh pers. comm - 7th December 1998, UBC, Green College lecture series), it is possible to form complex, yet still descriptive and transparent relationships between attributes and descriptors. In the example rule above, the variable current strength is designated a fuzzy variable with member sets *strong* and *not strong* (Fig. 5.1).

Whilst not all rules in the model use fuzzy definitions, the connection between fuzzy variables and their member sets provides the direct link for combining quantitative and qualitative knowledge and expressing associated uncertainty. They are the key to achieving quantitative output from qualitative understanding as will be shown later. Fuzzy rules avoid the impractical and almost impossible task of attempting to relate information in a purely quantitative way, whilst still being able to describe continuous functions. Interconnected associations between fuzzy variables can be conveniently expressed using a Fuzzy Associative Memory (FAM) map (Fig. 5.2). Each box on the FAM map represents one rule in the fuzzy system.

Definitions of fuzzy variables used for input to CLUPEX are provided in Appendix 5.2.

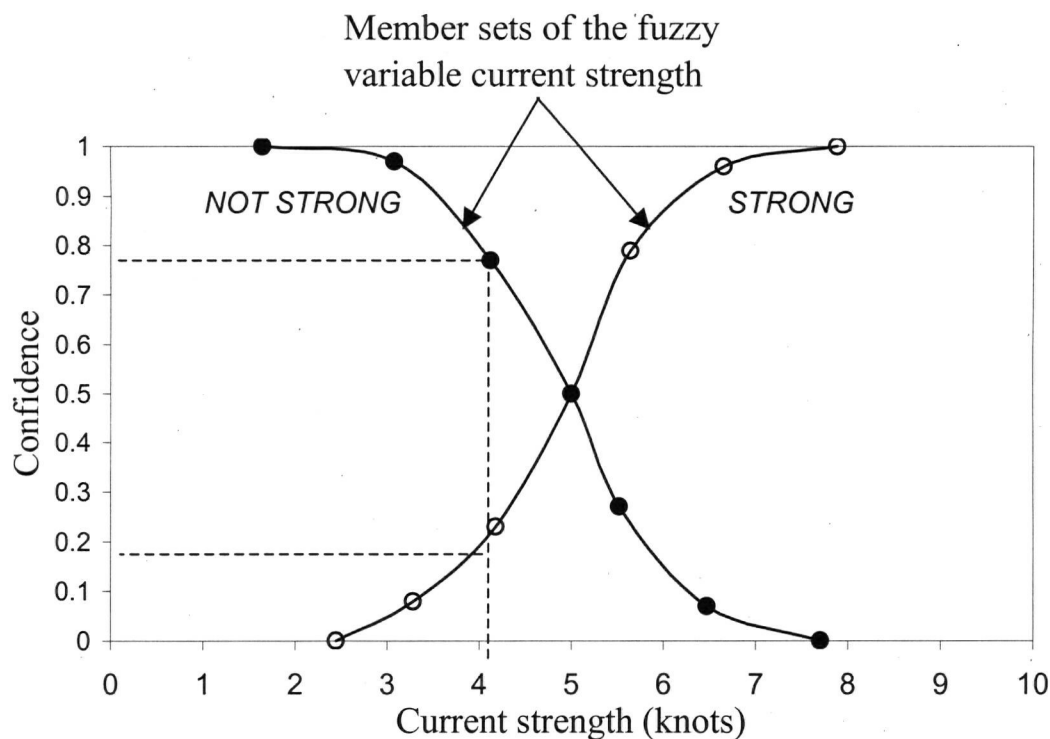


Figure 5.1 Membership functions of fuzzy sets on the fuzzy variable 'Current Strength'. The member sets are the linguistic concepts: *strong* and *not strong*. The confidence on the Y-axis shows our degree of belief in the linguistic concepts. For example, when current strength is 4 knots, we are 0.8 confident that current strength is *not strong* and also 0.2 confident that current strength is *strong*. Both pieces of information are used simultaneously to make conclusions, and thus the use of fuzzy sets provides ability to implicitly capture uncertainty. The value of current strength whose membership (confidence) is 1, is called the **supremum** value. The range of current strength values contained by a fuzzy set is called the **support**.

		STOCK SPATIAL RANGE				
AGE STRUCTURE	<i>Immature</i>	Collapsed	Restricted	Restricted	Intermediate	Intermediate
	<i>Adolescent</i>	Collapsed	Restricted	Intermediate	Fulfilled	Fulfilled
	<i>Mature</i>	Collapsed	Restricted	Intermediate	Fulfilled	Max. capacity
		<i>Very small</i>	<i>Small</i>	<i>Medium</i>	<i>Large</i>	<i>Huge</i>
		STOCK SIZE				

Figure 5.2 FAM map associating stock size and age structure with spatial range occupied by the stock. Each box in the map represents one rule in the expert system. Each element of the variables age structure and stock size are previously represented as fuzzy sets on their respective fuzzy variables.

Relative influence of attributes - hierarchy and trade-offs

A 'weight of evidence' approach is used to impose hierarchy in the degree of influence each attribute has on determining the resulting structure, dynamics and distribution of shoals. The method principle assumes that the more frequently an attribute is mentioned, the higher its importance relative to other contributing factors.

Weight is applied by assigning the THEN statements of each rule an associated confidence factor that is comprised of the sum of two parts; interviews and literature (each of which are given equal importance as previously mentioned). For example, THEN statements of rules associating predator abundance with shoal packing density have a confidence factor of 0.19 that is derived as follows:

$$\text{Item confidence} = (A_{\text{men}}/D_{\text{ask}})*0.45 + (A_{\text{dis}}/D_{\text{dis}})*0.45$$

$$(7/31)*0.45 + (8/41)*0.45 = 0.19$$

(A_{men}): No. of interviewees mentioned effect of predators abundance (attribute) on packing density (descriptor) = 7

(D_{ask}): No. of interviewees asked about effects on packing density = 31 (*Note: all interviewees asked about all descriptors*)

(A_{dis}): No. of papers discussing effect of predators abundance on packing density = 8

(D_{dis}): No. of papers that discussed effects on packing density = 41

A combined uncertainty of 10% is assumed for all rules, thus the maximum confidence THEN statements in a rule can achieve is 0.9.

During operation, confidence assigned to each THEN statement propagates through the system adding confidence to the output descriptor. Those statements with higher confidence carry more 'weight' and have greater effect. This becomes evident during the process of de-fuzzification whereby a discrete numeric value is obtained from the fuzzy output (see later, 'Predicting structure, dynamics and distribution'). The method used to calculate the final confidence as rules propagate through the system is detailed in Appendix 5.3.

The 'weight of evidence' approach further substitutes as a means of representing behavioural trade-offs that occur when herring balance potentially conflicting forces. For instance, since the effect of predators abundance on packing density has a higher confidence associated with it (Conf. = 0.19) than the effect of feeding competition (Conf. = 0.01), predators will have a greater influence on packing density even during competitive interactions. Such a trade-off is manifest

by increasing shoal packing density with the primary intention of deterring predators. Supplemental to this are specific rules for mimicking behavioural trade-offs. These rules have two or more conditions in the IF part of their statements linked by an AND. For example:

IF life phase ocean feeding
AND predators abundant
AND hunger status **low**
THEN Location shift **likely to occur**

IF life phase ocean feeding
AND predators abundant
AND hunger status **high**
THEN Location shift **may occur**

Operational logic, including rules and commands are also applied to define how the model operates under specific circumstances; in certain scenarios rules may be ignored whilst others are followed, or variables may be pre-assigned (in particular, when they are deemed of low importance). In addition, the user may be offered placebos (choices that do not lead to any conclusions) or the opportunity to assign low importance to a particular factor. This provides the option of choosing to exclude or reduce the influence of certain attributes. However, if the user answers 'not sure', an effort is made to assign a default choice/value where knowledge is available.

Seasonal changes in internal motivation

Temporal changes in motivational state are modelled by assigning a group of 'life-priority' rules that designate behavioural priorities for feeding, avoiding predators, reproduction and energy saving during each life stage. The designations of priority are utilised in a pseudo-weighting method that applies weight to a specific variable used to represent that priority. For example:

'Life-priority' rule

IF life phase overwintering
THEN feeding priority low
AND avoid **predation priority high**
AND reproduce priority medium
AND energy saving priority medium

Pseudo-weight rule

IF avoid **predation priority high**
THEN [actual pred. abund.] = [input pred. abund.]*[HIGHWEIGHT]

In this example, the effect of the pseudo-weight is to artificially increase the abundance of predators. The crux of the method is the assumption that increasing the abundance of predators equates to increased risk of predation. The effect of artificially increasing the abundance of predators is manifest in changes in the structure, dynamics and distribution of shoals. The same

approach is used for other 'life-priorities'. It is recognised that this method of weighting is not the most suitable. A better solution would be a weighting scheme that performs operations directly on confidence values and/or uses variables for weights used in defuzzification. Unfortunately, constraints of the development software do not permit this, thus, the pseudo-weighting method offers a pragmatic solution.

Predicting structure, dynamics and distribution

During operation, implementation of a forward chaining inference strategy forces the system to examine each rule in sequence. On initiation of a query, the expert system prompts a user for an input. From this point onwards, as each rule is examined, the system employs a recursive strategy, backward chaining through the knowledge-base to derive facts that satisfy IF conditions of rules so that inferences can be made from their THEN conditions. When no further inferences can be made, forward chaining occurs and the user is again prompted for an answer. Inferencing during backward chaining adds 'intelligence' to the system ensuring the user is asked only those questions pertinent to draw conclusions relevant to conditions specified.

During inferencing, rules that use variables defined as fuzzy sets in the IF part are followed in parallel and to a partial extent, since at any time several rules may be true to a certain degree. The confidence in each is propagated through the system and combined with the confidence assigned in the THEN statement using a series of equations (Appendix 5.3) resulting in each choice, or fuzzy set of an output descriptor accumulating a final confidence. For example, the system makes the fuzzy conclusion that shoal size is *small* (Conf. = 0.2), *medium* (Conf. = 0.6) and *large* (Conf. = 0.3). The process of obtaining a single non-fuzzy value as output from the fuzzy conclusion is called de-fuzzification. The method used here is weighted-average de-fuzzification, and is based on a multiplication between the degree of membership to the output fuzzy sets and the supremum value (see Figure 5.1 caption for definition) of each set (Fig. 5.3) (Meech and Kumar, 1995). By applying the same procedure to maximum and minimum ranges associated with each of the fuzzy sets of output descriptors, a range around the discrete output value is obtained (Fig. 5.3). Using the example in Fig. 5.3, the discrete de-fuzzified weighted output would be calculated as follows:

$$\text{Mean} = [(0.2 * \text{Small}_{\text{sup}}) + (0.6 * \text{Med}_{\text{sup}}) + (0.3 * \text{Large}_{\text{sup}})] / \text{sum of confidence} \quad (1.1)$$

$$\text{Range min.} = [(0.2 * \text{Small}_{\text{min}}) + (0.6 * \text{Med}_{\text{min}}) + (0.3 * \text{Large}_{\text{min}})] / \text{sum of confidence} \quad (1.1)$$

$$\text{Range max.} = [(0.2 * \text{Small}_{\text{max}}) + (0.6 * \text{Med}_{\text{max}}) + (0.3 * \text{Large}_{\text{max}})] / \text{sum of confidence} \quad (1.1)$$

Supremum values used as weights are obtained from an extensive literature review of published values observed in the field; a detailed record of which is kept in the Knowledge-base (see **Select Options** menu - *View original data forms* - Structure and distribution quantitative data).

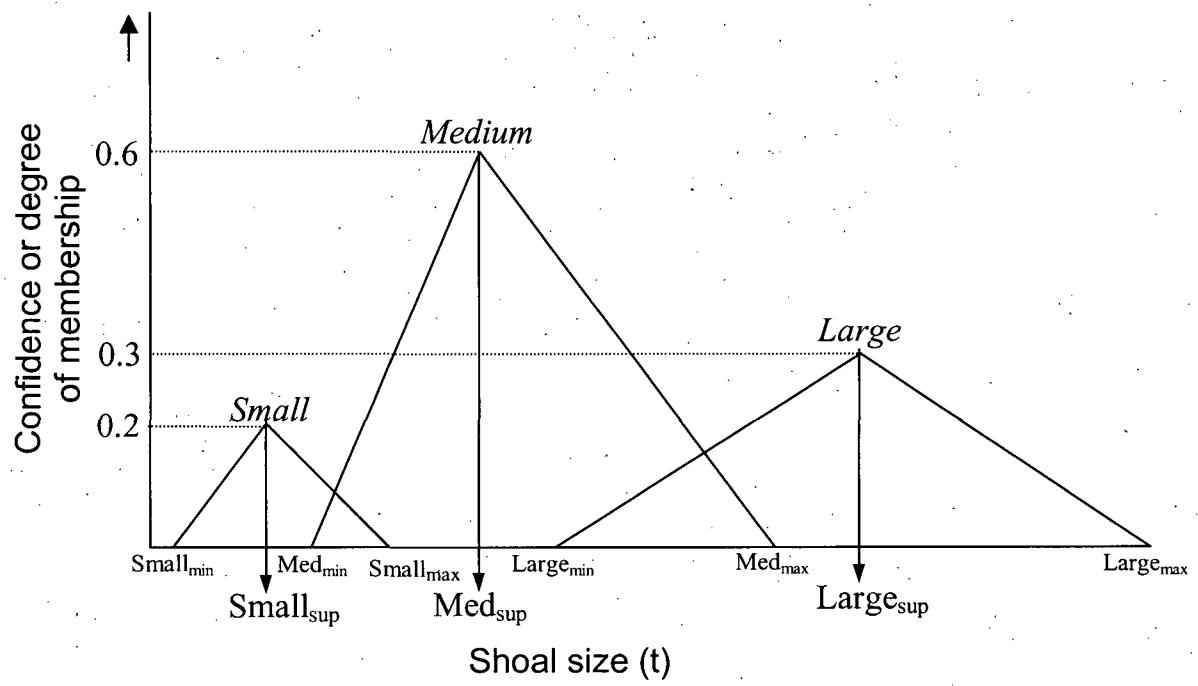


Figure 5.3 Output fuzzy sets for shoal size used in de-fuzzification. $Small_{sup}$, represents the supremum value of shoal size for the fuzzy set *small*. Similarly, $Small_{min}$ to $Small_{max}$ represents the support of the fuzzy set *small*.

5.3 Operation and explanation facility

Note: For specific information on how to operate CLUPEX and instructions on the facility for explaining how the model derives its predictions, see the hypertext file "Readme.html". You can view the file using any web browser. Alternatively, see Appendix 5.1 for a printed version of the Readme file..

Two examples are used to demonstrate operation and reasoning leading to predictions from CLUPEX. The first example makes predictions for overwintering Pacific herring, showing in detail how facts input by the user and knowledge from rules are utilised during inferencing to make predictions. The second example makes predictions for ocean feeding Norwegian spring spawning herring. It is less detailed and focuses on highlighting the intelligent nature of the system by comparing how the run differs from the first example.

During inferencing a forward chaining strategy is used. Each rule is examined in sequence and only when a rules premise (IF part) cannot be determined from knowledge already known (either from facts input by the user or by backward chaining from a rule's consequent (THEN statements)) does the model ask the user for input. In this manner, firing of rules is to a certain extent dependent on the order of rules. In CLUPEX, no attempt is made to order rules according to any particular way, and thus, rules can be added freely without altering the overall structure or operation of the model. However, this aspect and the use of custom screens to ask multiple inputs from users, requires a configuration file as a necessary, alternative way of organising the order of questions asked of the user. The consequence of using this approach is that firing of rules during backward chaining is not entirely intuitive. In the detailed example of the overwintering Pacific herring given below, I have structured the linkages between facts and rules to more clearly emphasise how information is derived for each prediction.

The inference process can be viewed as operating like a multi-layered decision tree. There are four basic layers determining which rules fire and how information is derived;

1. **Information from facts** - information on attributes asked by CLUPEX and input by the user via custom forms. Asked only when information cannot be derived by chaining.
2. **Rules from facts** - rules fired when the IF part is found true according to facts input by the user. Conclusions from the THEN statements adds further information which may be utilised by other rules;
3. **Rules from rules** - rules fired when IF part is found true by backward chaining from rules previously found to be true. Several rules may cause the firing of a particular rule (**Rules fired from multiple rules**).
4. **Facts from rules** - facts derived from rules found true during backward chaining.

During inferencing the confidence assigned to each THEN statement of a rule is combined with that of the IF part in a running series such that, as each rule fires, descriptors accumulate confidence. The method of combining confidence is described in Appendix 5.3. In example one below, a running table (Table 5.1) is used to trace the confidence assigned to each descriptor as each rule fires.

Note that in the examples, attributes used in rules are typed in lower case whilst descriptors are typed in upper case. For each example a brief narrative of the system operation is provided.

Those parts marked with a vertical bar (as shown here) at the side indicate operational elements of CLUPEX. They include the information from facts, rules from facts, rules from rules, facts from rules and the input and output screens.

Example 1: Overwintering Pacific herring

Linkages between facts and rules are mapped in Figure 5.4 and full details of how information propagates through the system are given in following text. Each rule found to be true is shown, together with the notes and references specific to that rule. A Knowledge-base ID# provides a cross-reference to the knowledge database where more information is contained on how each rule was derived. Note that the references cited in CLUPEX use two formats that relate to different reference sources:

- (i) [#] Name : reference to interviewee (see **Select Options** menu - *View original data forms* - Interview details)
- (ii) [ref##] Name Date: reference to literature source (see **Select Options** menu - *View original data forms* - References).

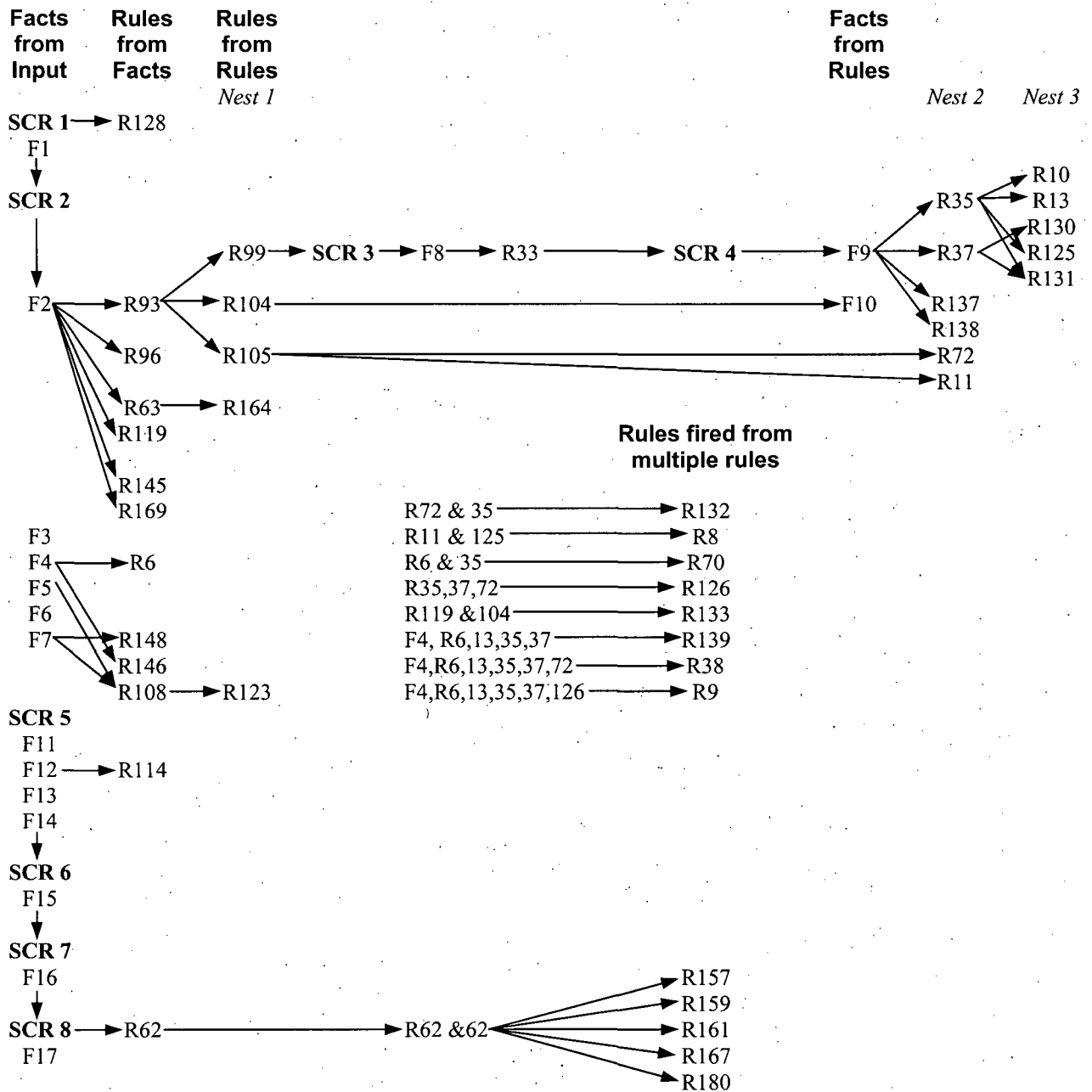


Figure 5.4 Linkages between facts and rules during an example run for overwintering Pacific herring. Abbreviations: SCR# = Custom screen asked for user input; F = Fact; R = Rule. Nest # - nested sequence of rules being fired (see text for full details).

The user opens CLUPEX, is presented with a brief opening dialogue and then selects to run the expert system.

> RUN CLUPEX

> START CONFIGURATION FILE

Configuration file read and CLUPEX starts by asking the location (Fig 5.5)

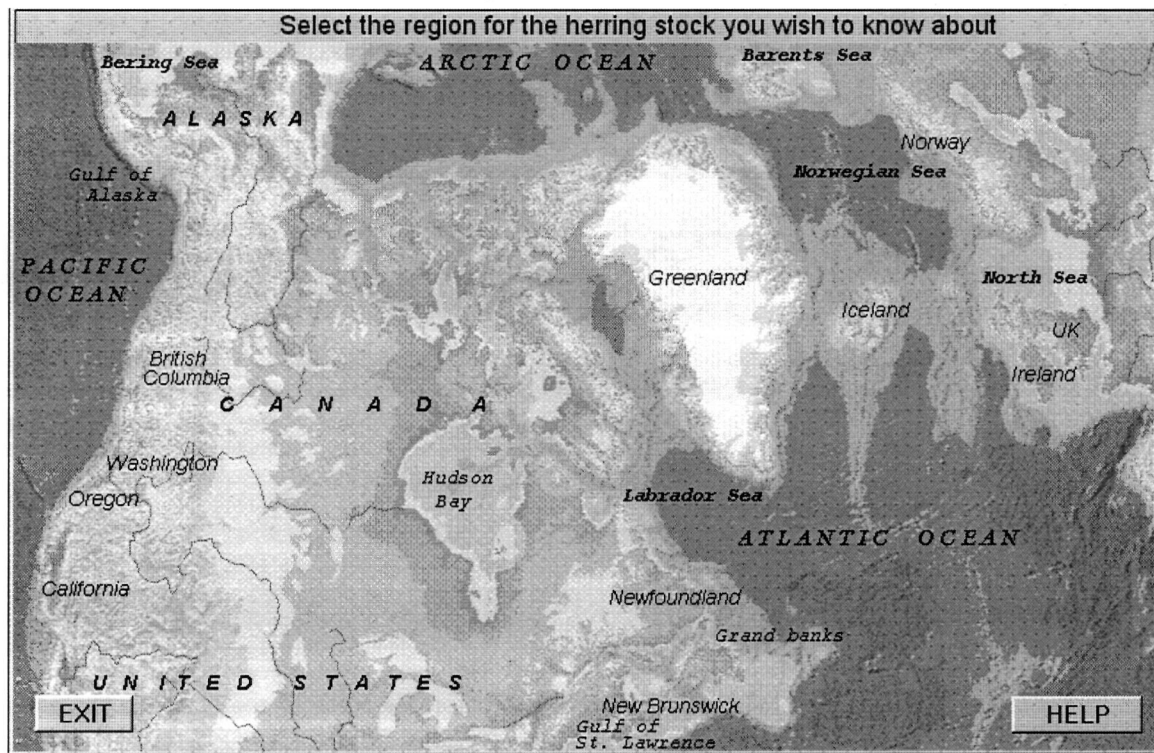


Figure 5.5 Location map used to derive which herring species the user is interested in.

User select region on the map relating to the location of the herring species which they wish to know about. User selects Pacific ocean.

Facts derived from input

F1: Qualifier 59 choices set; Location = Pacific ocean (conf=1)

Rules derived from Facts

- Rule 128 (SPID2) found to be TRUE from F1

IF:

Location Pacific ocean

THEN:

Species Pacific Herring (Clupea pallasii)

NOTE: Operational rule to determine the species of herring based on a map of the oceans.

Calculation of Fuzzy Confidence for Rule 128:

IF confidence

condition 1 conf=1.000

THEN added...

Table 5.1 Running table: calculation of confidence for each descriptor.

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
Species	60	Pacific herring (<i>Clupea pallasii</i>)	0.000	1.000	1.000

Configuration file read again; prompts user with general characteristics screen (Fig 5.6) for input. Six facts are derived from the input.

GENERAL CHARACTERISTICS

Select the Life phase from the menu below:

☐ Off-shore migrating
☐ Ocean feeding
☐ On-shore migration
☒ Overwintering

☐ Pre-spawning
☐ Spawning
☐ Immediate post-spawned

Do you wish to know about a specific time of day?

☒ Yes

Day

Please check the box below after making your selection

☐ NO

☒ Done

Enter the number of year classes in the stock, a rough estimate of the local abundance of fish in the area you are considering and select a description that best describes the **relative stock size**:

YEAR CLASSES (1-15)

8

LOCAL ABUNDANCE (tonnes)

20000

RELATIVE STOCK SIZE

Tip

very small

small

medium

large

very large

EXIT

Known info.

HELP

OK, all done!

Figure 5.6 General characteristics input screen.

Facts derived from input

- F2: Qualifier 2 choices set; Life phase = overwintering (conf=1)
- F3: Qualifier 55 choices set; Importance of time of day (special case of time in which to know answer) = important (Conf=1)
- F4: Qualifier 1 choices set; Time of day = Day (Conf=1)
- F5: Variable [AGECLASS] set to 8 (Conf=1) resulted in qualifier 28 value set; AGE STRUCTURE OF STOCK (number of age classes or approx oldest age) = mature
- F6: Variable [INPUTSTOCK] set to 20,000 (Conf=1)
- F7: Qualifier 54 choices set; RELATIVE STOCK SIZE = medium (Conf=1)

Facts input by the user are compared against rules in the CLUPEX rule base to see if they satisfy the IF conditions. Those found to be true are shown below.

Rules derived from Facts

From FACT 2

- Rule 93 (PRIORITY3) found to be TRUE from F2

IF:

Life phase overwintering

THEN:

*Feeding status barely feeding
and Feeding priority low
and Avoid predation risk priority high
and Reproduce priority medium
and Energy saving priority high*

NOTE:

(Knowledge-base #18,19,20,72,45): These "priority" rules emphasise seasonal differences in motivational state of herring. In each life phase herring trade-off survival goals including energy saving, risk avoidance, feeding and reproduction. Changes in the importance of each goal affect the underlying structure and distribution of shoals through the application of a pseudo-weighting method. For example: during overwintering when herring are feeding only rarely and opportunistically, feeding priority is set at low. A weight is applied that changes the importance of food in determining the structure and distribution of shoals. At the same time, risk avoidance has a high priority, and as a consequence a weight is applied to alter the abundance of predators (this assumes that predation risk is proportional to predators abundance).

REFERENCE:

[31] Mackinson, [ref#32] Hay 1985, [ref#35] Hourston and Haegle 1980, [ref#48] Nøttestad et al. 1996, [ref#171] Nøttestad and Axelsen 1997, [ref#208] DFO 1991, [ref#82] Winters 1977, [ref#184] Ware 1985, [ref#83] Huse and Ona 1996, [ref#60] McCarter et al. 1994, [ref#167] Pitcher and Parrish 1993, Parsons and Hodder 1975.

Calculation of Fuzzy Confidence for Rule 93:

IF confidence

Condition 1 confidence=1.000

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
Feeding status	3	barely feeding	0.000	1.000	1.000
Feeding priority	30	low	0.000	1.000	1.000
Avoid predation risk priority	31	high	0.000	1.000	1.000
Reproduce priority	32	medium	0.000	1.000	1.000
Energy saving priority	33	high	0.000	1.000	1.000

- Rule 96 (LIFEMAT) found to be TRUE from F2

IF:

Life phase on-shore migrating OR spawning OR off-shore migrating OR ocean feeding OR overwintering OR immediate post-spawned AND Life phase NOT pre-spawning

THEN:

Pre-spawning maturation stage (British Columbia herring ^roe categories^) low importance

NOTE:

Operational rule: when life phase is not pre-spawning then maturation stage has no influence on final distribution and structure.

Calculation of Fuzzy Confidence for Rule 96:

IF confidence

Condition 1 conf=1.000

Condition 2 conf=1.000

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
Pre-spawning maturation stage	16	low importance	0.000	1.000	1.000

- Rule 63 (ASSOC3) found to be TRUE from F2

IF:

Life phase pre-spawning OR overwintering

THEN:

SHOALS ^ASSOCIATED WITH SPECIFIC FEATURES^ (PHYSICAL/ OCEANOGRAPHIC) passes with high flushing rate and inlets & bays

NOTE:

(Knowledge-base #70,77): During periods where herring are 'holding' in specific areas (e.g. overwintering or early pre-spawners), shoals form strong association with particular oceanographic, topographical and substrate features. Frequently, very large shoals (thousands tonnes) are found located in specific areas that offer high rates of water exchange (passes between islands) or in bays, inlets or fjords (possible food retention areas). Association with these features is assumed to offer advantages such as potential feeding sites, energy saving (in deep cold fjords) and also areas that may offer preferred substrate types.

REFERENCE:

[3] Nøttestad, [31] Mackinson, [7] McCarter, [29] Wilson, [16] Redford, [17] Malatestinic, [18] Reid, [11] Webb, [12] Armstrong, [19] Heglund, [13] Chalmers, [15] Thomas, [22] Lenic, [21] Boroevich, [24] Pierce, [23] Carr, [28] Hunt, [ref#101] Maravelias and Haralabous 1995, [ref#198] Slotte 1998, [ref#208] DFO 1991, [ref#231] Blaxter and Holliday 1969 - (Jakobsson 1961), Reid 1995, Maravelias 1997, Maravelias and Reid 1995, Maravelias and Reid 1997, Maravelias et al. 1997, Reid et al. 1993

Calculation of Fuzzy Confidence for Rule 63:

IF confidence

Condition 1 conf=1.000

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SHOALS ASSOCIATED WITH SPECIFIC FEATURES	43	passes with high flushing rate and inlets & bays	0.000	1.000	1.000

- Rule 119 (LOWFOOD) found to be TRUE from F2
IF:
Life phase pre-spawning OR spawning OR overwintering

THEN:
[INFOOD] IS GIVEN THE VALUE 0.5

NOTE: Operational rule: if the life phase is pre-spawning, spawning or overwintering; herring barely feed and food is of low importance. This is directly represented by applying a low input value to the variable food abundance.

Calculation of Fuzzy Confidence for Rule 119:

IF confidence

Condition 1 conf=1.000

THEN added...

Variable [INFOOD] set to 0.500 (conf=1)

- Rule 145 (NORES1) found to be TRUE from F2

IF:
Life phase NOT ocean feeding

THEN:
^^LOCATION SHIFT^^ there is no result for this descriptor
and ^^STOCK DISTRIBUTION EXTENT^^ there is no result for this descriptor

NOTE: Operational rule that ensures the descriptor is sent to the output file even when there is no result.

Calculation of Fuzzy Confidence for Rule 145:

IF confidence

Condition 1 conf=1.000

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
LOCATION SHIFT	51	there is no result for this descriptor	0.000	1.000	1.000
STOCK DISTRIBUTION EXTENT	56	there is no result for this descriptor	0.000	1.000	1.000

- Rule 169 (HABITAT14) found to be TRUE from F2

IF:
Life phase NOT spawning

THEN:
[SPAWNSUB] IS GIVEN THE VALUE 0

NOTE:
Operational rule for use in graphical display of shoals. If herring shoals are associated with a specific ocean/ topography/substrate feature a variable is switched from 0-'off' to 2-'on and associate'.

Calculation of Fuzzy Confidence for Rule 169:

IF confidence

Condition 1 conf=1.000

THEN added

Variable [SPAWNSUB] set to 0 (conf=1)

From FACT 4

- Rule 6 (TOD8) found to be TRUE from F4

IF:

Time of day Day

THEN:

^^PACKING DENSITY^^ medium
and SHOAL DEPTH deep AND bottom
and ^^INTERNAL DYNAMICS^^ schooling
and ^^EASE OF CAPTURING^^ A SCHOOL low
and ^^NEAREST NEIGHBOUR DISTANCE^^ medium AND high
and ^^Mean INTER-SCHOOL distance^^ (average distance among all schools)
medium AND high

NOTE:

(Knowledge-base #6,2,1,4,109,106): Typical diurnal behaviour of herring is to perform vertical migration. At dusk schools rise to the surface waters and disperse to form loose shoals, that may spread out very thinly during the night. At daybreak fish coalesce to reform more compact schools and dive to deeper water. This behavioural pattern may be modified from region to region and depend on other factors such as feeding conditions or maturation state. Distribution studies suggest that distinct shoals may still occur at night but clusters of shoals are less patchily distributed at night than day. Distance to nearest neighbour shoal may actually be reduced through dispersion.

REFERENCE:

[1] Misund, [3] Nøttestad, [7] McCarter, [12] Armstrong, [19] Heglund, [6] Ware, [15] Thomas, [22] Lenic, [21] Boroevich, [24] Pierce, [23] Carr, [28] Hunt, [31] Mackinson, [4] Melle, [8] Hay, [10] Gordon, [17] Malatestinic, [18] Reid, [11] Webb, [26] Jim, [13] Chalmers, [ref#43] Robinson et al. 1995 -(Furness 1982; Howick and Obrien 1983; Bailey 1989; Pitcher and Wyche 1983), [ref#51] Buerkle and Stephenson 1990, [ref#168] Radakov 1973., [ref#20] Blaxter 1985, [ref#21] Mohr 1971, [ref#52] Burton 1990, [ref#56] Mathieson et al. 1983, [ref#123] Neilson and Perry 1990, [ref#175] Butcher, [ref#208] DFO 1991, [ref#231] Blaxter ad Holliday 1969 - (Radakov 1960), [ref#8] Misund 1990, [ref#111] Misund 1993c, [ref#77] Tester 1938, [ref#178] Michalsen et al. 1996, [ref#154] Gerlotto and Petitgas 1991, [ref#246] Mackinson et al. 1998, [ref#59] Thorne 1977, [ref#75] Fréon et al. 1996.

Calculation of Fuzzy Confidence for Rule 6:

IF confidence

Condition 1 confid=1.000

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
Packing Density	34	Medium	0.000	0.220	0.220
SHOAL DEPTH	41	deep	0.000	0.370	0.370
		Bottom	0.000	0.370	0.370
INTERNAL DYNAMICS	37	Schooling	0.000	0.900	0.900
EASE OF CAPTURING	39	low	0.000	0.250	0.250
A SCHOOL					

NEAREST NEIGHBOUR DISTANCE	49	Medium	0.000	0.080	0.080
		high	0.000	0.080	0.080
Mean INTER-SCHOOL distance	50	Medium	0.000	0.150	0.150
		high	0.000	0.150	0.150

From FACT 7

- Rule 148 (STOCKNND2) found to be TRUE from F7

IF:

^^RELATIVE STOCK SIZE^^ medium

THEN:

^^NEAREST NEIGHBOUR DISTANCE^^ medium

NOTE:

(Knowledge-base #114): Study of clustering in Sardinella schools showed that the number of schools per unit length inside a cluster (here same as the NND between shoals) was correlated with population abundance.

REFERENCE:

[ref#191] Petitgas and Samb 1998.

Calculation of Fuzzy Confidence for Rule 148:

IF confidence

Condition 1 conf=1.000

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
NEAREST NEIGHBOUR DISTANCE	49	Medium	0.080	0.090	0.163

From FACTS 2 & 4.

- Rule 146 (NORES2) found to be TRUE from F2 & F4

IF:

*Life phase pre-spawning OR spawning OR overwintering
and Time of day NOT Night OR Dusk*

THEN:

*^^SEGREGATION OF SIZE CLASSES^^ / AGE CLASSES there is no result for
this descriptor*

NOTE:

Operational rule that ensures the descriptor is sent to the output file even when there is no result.

Calculation of Fuzzy Confidence for Rule 146:

IF confidence

Condition 1 conf=1.000

Condition 2 conf=1.000

total IF conf=1.000

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SEGREGATION OF SIZE CLASSES	42	there is no result for this descriptor	0.000	1.000	1.000

From FACTS 5 & 7

- Rule 108 (STOCK8) found to be TRUE from F5 & F7

IF:

*^RELATIVE STOCK SIZE^ medium
and AGE STRUCTURE OF STOCK (number of age classes or approx oldest age)
adolescent OR mature*

THEN:

^STOCK FULFILMENT OF RANGE^ intermediate

NOTE:

(Knowledge-base #86,92): The extension of the stock in to its potential range is principally a combination of two factors; the age structure of the stock and the total population size. Age structure is fundamental since an element of learning may be involved in migration and colonisation of habitats. Only a very large population with a diverse age structure is likely to achieve its full potential range.

REFERENCE:

[1] Misund, [2] Fernö, [3] Nøttestad, [ref#36] Hourston 1980, [ref#45] Sinclair et al, 1985, [ref#227] Helfman and Schultz 1984, [ref#191] Petitgas and Samb 1998, Bergstad et al. 1991, Sinclair and Isles 1985.

Calculation of Fuzzy Confidence for Rule 108:

IF confidence

Condition 1 conf=1.000

Condition 2 conf=0.750

total IF conf=0.750

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
STOCK FULFILMENT OF RANGE	53	intermediate	0.000	0.230	0.173

Rules derived by chaining from other rules

When a rule is found to be true it leads to others being fired, some of which are also found to be true. In this example, this mechanism leads to a 'nested' structure with 3 nests. For clarity, a different font is used for each nest; Nest 1: Times Roman, Nest 2: Arial, Nest 3: memorandum.

Nest 1

- Rule 99 (RISKWT1) found to be TRUE from Rule 93

IF:

Avoid predation risk priority high

THEN:

[FZPREDAB] IS GIVEN THE VALUE [INPRED][HIGHWT]*

NOTE:

Operational rule: at different stages in the adult life phase, "priority" rules are assigned to assert changes in motivational priorities to either feed, save energy, avoid predation risk or reproduce. The affect of these priorities on the structure and distribution of shoals is manifest by applying a weight factor (high, medium, low) that artificially changes certain attributes that correspond with the priority. For example - the effects of 'avoid risk priority' is manifest by changing the abundance of predators. This assumes that predation risk is proportional to the abundance of predators. The same method is applied to food abundance to reflect changes in feeding priority.

Variable [INPRED] required by Rule 99. However, [INPRED] relates only to the abundance of aquatic predators, so first the system needs to know what type of predators are present. Backward chaining finds that Rule 33 tells the system what predators are present, but it cannot derive the answer so the user is asked (Fig 5.7). Next the user is asked to specify the abundance of predators [INPRED] (Fig 5.8). Note that the value of [HIGHWT] is fixed at 1.5

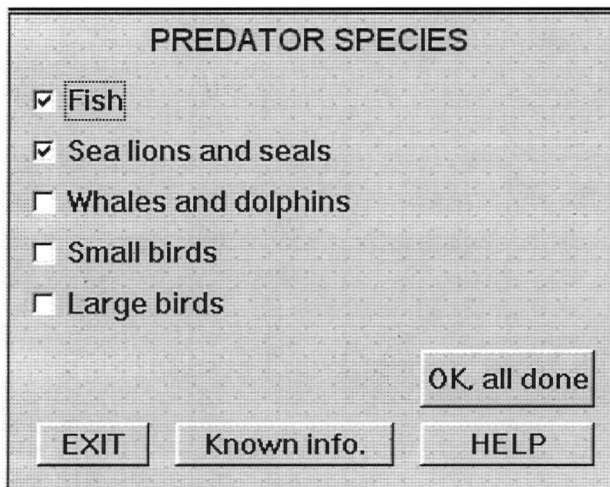


Figure 5.7 Input of predator species.

Facts derived from input

F8: Qualifier 10 choices set; Predator species = Fish AND sea lions and seals (conf=1)

Rules derived from Facts

- Rule 33 (PREDID1) found to be TRUE from F8

IF:

Predator species Fish OR sea lions and seals OR whales and dolphins

THEN:

Type of predator aquatic predator (fish, sea lions, whales etc)

NOTE:

(Knowledge-base #40): Operational rule to determine type of predator: Aquatic predator or Avian predator.

Calculation of Fuzzy Confidence for Rule 33:

IF confidence

Condition 1 conf=1.000


THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
Type of predator	11	aquatic predator	0.000	1.000	1.000

PREDATORS ABUNDANCE

using the slide bar please indicate a the realtive abundance of predators on a hypothetical scale of 0-10 (where 10 is most abundant)

4.0



012345678910

EXIT
Known info.
HELP
OK, all done

Figure 5.8 Abundance of aquatic predators input screen.

Calculation of Fuzzy Confidence for Rule 99:

IF confidence

Condition 1 conf=1.000

THEN added

Variable [INPRED] set to 4 (conf=1)

Variable [FZPREDAB] set to 6 (conf=1)

Fact 9 derived from Rule 99

F9: Using fuzzy variable [FZPREDAB] qualifier 12 has values set; Abundance of aquatic predators = frequent AND common

Nest 2

- Rule 35 (AQPREDAB1) found to be TRUE from F9 and Rule 33

IF:

Type of predator aquatic predator (fish, sea lions, whales etc)
and Abundance of aquatic predators common

THEN:

^^PACKING DENSITY^^ medium AND high
and ^^SHOAL SIZE^^ medium AND large
and ^^SHOAL SHAPE^^ spheroid AND layer

and ^^INTERNAL DYNAMICS^^ schooling
 and ^^DYNAMIC TENDENCY^^ high
 and ^^NEAREST NEIGHBOUR DISTANCE^^ low
 and ^^AVERAGE SWIMMING SPEED^^ OF ALL FISH IN A SHOAL high
 and SHOAL DEPTH deep AND bottom

NOTE:

(Knowledge-base #36,43,34,35,33,31,41,32): Typical anti-predator response to increased risk of predation (abundance of predators used here as an index of risk of predation) is for fish within a school to reduce their distance to neighbour, thus increasing the packing density. They form polarised co-ordinated schools, as individuals within the school start to swim faster and pack tighter and dive to deeper water. Small and medium sized shoals may typically form spheroid shape (thought to minimise detection) whilst very large schools may remain in layers (their great size offering protection perhaps from intimidation). Size of schools increases through joining events and individuals gain benefits from dilution and attack abatement. When predation risk is lower, schools may split as individual seek the foraging benefits associated with smaller schools. In the presence of predators schools may display increased activity, events such as splitting and joining of schools occurring more frequently than when predation is low. Schools may become more tightly clustered as the distance between schools (NND) is reduced as schools coalesce to form larger schools. Close neighbours offers greater possibilities for school size adjustments.

REFERENCE:

[1] Misund, [3] Nøttestad, [17] Malatestinic, [18] Reid, [12] Armstrong, [19] Heglund, [22] Lenic, [4] Melle, [2] Fernö, [20] Ellis, [13] Chalmers, [15] Thomas, [6] Ware, [ref#90] Keenlyside 1955, [ref#156] Fréon et al. 1992, [ref#4] Pitcher et al. 1996, [ref#170] Similä and Ugarte 1993, [ref#171] Nøttestad and Axelsen 1997, [ref#218] Major 1978, [ref#221] Hamilton 1971, [ref#231] Blaxter and Holliday 1969, [ref#87] Pitcher and Partridge. 1979, [ref#167] Pitcher and Parrish 1993, [ref#209] Lima and Dill 1990, [ref#99] Morgan 1988, [ref#121] Magurran 1990, [ref#129] Krause et al. 1998, [ref#208] DFO 1991, [ref#214] Pitcher et al. 1986, [ref#216] Krause and Godin 1994, [ref#219] Krause et al. 1998, [ref#223] Neill and Cullen 1974, [ref#225] Hager and Helfman 1991, [ref#237] Godin 1986, [ref#246] Mackinson et al. 1998, Morgan and Colgan 1987, Godin et al. 1988.

Calculation of Fuzzy Confidence for Rule 35:

IF confidence
 Condition 1 conf=1.000
 Condition 2 conf=0.333
 total if conf 0.333
 THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
PACKING DENSITY	34	medium	0.220	0.190	0.269
		high	0.000	0.190	0.063
SHOAL SIZE	45	medium	0.000	0.210	0.070
		large	0.000	0.210	0.070
SHOAL SHAPE	44	spheroid	0.000	0.130	0.043
		layer	0.000	0.130	0.043
INTERNAL DYNAMICS	37	schooling	0.900	0.090	0.903
DYNAMIC TENDENCY	36	high	0.000	0.150	0.050
NEAREST NEIGHBOUR DISTANCE		low	0.000	0.040	0.013
AVERAGE SWIMMING SPEED	38	high	0.000	0.030	0.010
SHOAL DEPTH	41	deep	0.370	0.110	0.393
		bottom	0.370	0.110	0.393

- Rule 37 (AQPREDA3) found to be TRUE from F9 & Rule 33

IF:

Type of predator aquatic predator (fish, sea lions, whales etc)
 and Abundance of aquatic predators frequent

THEN:

^^PACKING DENSITY^^ medium
 and ^^SHOAL SIZE^^ small AND medium
 and ^^INTERNAL DYNAMICS^^ schooling
 and ^^DYNAMIC TENDENCY^^ medium
 and ^^NEAREST NEIGHBOUR DISTANCE^^ medium

NOTE:

(Knowledge-base #36,43,35,33,31): Typical anti-predator response to increased risk of predation (abundance of predators used here as an index of risk of predation) is for fish within a school to reduce their distance to neighbour, thus increasing the packing density. They form polarised co-ordinated schools, as individuals within the school start to swim faster and pack tighter. Small and medium sized shoals may typically form spheroid shape (though to minimise detection) whilst very large schools may remain in layers (their great size offering protection perhaps from intimidation). Size of schools increases through joining events and individuals gain benefits from dilution and attack abatement. When predation risk is lower, schools may split as individual seek the foraging benefits associated with smaller schools. In the presence of predators schools may display increased activity, events such as splitting and joining of schools occurring more frequently than when predation is low. Schools may become more tightly clustered as the distance between schools (NND) is reduced as schools coalesce to form larger schools. Close neighbours, offers greater possibilities for school size adjustments.

REFERENCE:

[1] Misund, [3] Nøttestad, [17] Malatestinic, [18] Reid, [12] Armstrong, [19] Heglund, [22] Lenic, [2] Fernö, [4] Melle, [20] Ellis, [13] Chalmers, [15] Thomas, [6] Ware, [ref#90] Keenlyside 1955, [ref#156] Fréon et al. 1992, [ref#4] Pitcher et al. 1996, [ref#170] Similä and Ugarte 1993, [ref#171] Nøttestad and Axelsen 1997, [ref#218] Major 1978, [ref#221] Hamilton 1971, [ref#231] Blaxter and Holliday 1969, [ref#99] Morgan 1988, [ref#121] Magurran 1990, [ref#129] Krause et al. 1998, [ref#167] Pitcher and Partridge 1993, [ref#208] DFO 1991, [ref#214] Pitcher et al. 1986, [ref#216] Krause and Godin 1994, [ref#219] Krause et al. 1998, [ref#223] Neill and Cullen 1974, [ref#225] Hager and Helfman 1991, [ref#237] Godin 1986, [ref#246] Mackinson et al. 1998, Morgan and Colgan 1987, Godin et al. 1988.

Calculation of Fuzzy Confidence for Rule 37:

IF confidence
 Condition 1 conf=1.000
 Condition 2 conf=0.667
 Total IF conf =0.667
 THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
PACKING DENSITY	34	medium	0.269	0.190	0.362
HOAL SIZE	45	small	0.000	0.210	0.140
		medium	0.070	0.210	0.200
INTERNAL DYNAMICS	37	schooling	0.903	0.090	0.909
DYNAMIC TENDENCY	36	medium	0.000	0.150	0.100
NEAREST NEIGHBOUR DISTANCE	49	medium	0.163	0.040	0.185

Nest 3

- Rule 10 (PD3) found to be TRUE from Rule 35

IF:

^^PACKING DENSITY^^ high OR very high

THEN:

^^RELATIVE EXTENT^^/ AREA OCCUPIED small

NOTE:

(Knowledge-base #12,80): For a given shoal size, the relative extent/area of the shoals will change depending on the packing density of fish within the shoal, which in turn is partly dependent on the average swimming speed on fish within the shoal.

REFERENCE:

[4] Melle, [31] Mackinson, [ref#72] Petitgas and Levenez 1996.

Calculation of Fuzzy Confidence for Rule 10:

IF confidence

Condition 1 conf=0.063

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
RELATIVE EXTENT	35	small	0.000	0.900	0.057

- Rule 13 (SWSP3) found to be TRUE from Rule 35

IF:

^^AVERAGE SWIMMING SPEED^^ OF ALL FISH IN A SHOAL high

THEN:

^^PACKING DENSITY^^ medium

and ^^INTERNAL DYNAMICS^^ schooling

and ^^SHOAL SHAPE^^ horizontally elongated

NOTE:

(Knowledge-base #81,78,79): As swimming speed of individual decreases, the fish decrease their inter-fish distance, thereby reducing the overall packing density of the school. To keep co-ordinated at higher speed it is necessary for fish to school (polarised shoal, co-ordinated behaviour). At high swimming speeds and/or in fast currents shoal shape tends to be horizontal elongated 'cigar shape', presumably conferring hydrodynamic advantage.

REFERENCE: [1] Misund, [ref#87] Pitcher and Partridge 1979 - (Partridge, B.L. 1981; Partridge et al. 1980), [ref#208] DFO 1991, [ref#167] Pitcher and Partridge 1993, [ref#168] Radakov 1973 - (Tikhonov 1957, 1959), [ref#232] Breder 1967.

Calculation of Fuzzy Confidence for Rule 13:

IF confidence

Condition 1 conf=0.010

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
PACKING DENSITY	34	medium	0.362	0.060	0.362
INTERNAL DYNAMICS	37	schooling	0.909	0.050	0.909
SHOAL SHAPE	44	horizontally elongated	0.000	0.040	0.000

- Rule 130 (COHESION1) found to be TRUE from Rule 37

IF: ^^SHOAL SIZE^^ very small OR small

THEN: ^^SHOAL COHESION^^ low

NOTE:

(Knowledge-base #110): Definition of cohesion: "A more cohesive school is defined as one in which there are fewer stragglers from the group, fewer aggressive interactions between individuals and which has a smaller dispersion of fish with the shoals (lower packing density). Individuals in such a shoal would appear to behave in a more unified manner (schooling)". Experiment with differences in hunger level and predation by bass on bluntnose minnows showed that shoal cohesiveness increased as both shoal size increased and in the presence of a predator, and decreased as hunger level increased.

REFERENCE:

[ref#99] Morgan 1988.

Calculation of Fuzzy Confidence for Rule 130:

IF confidence
 Condition 1 confidence=0.140
THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SHOAL COHESION	47	low	0.000	0.030	0.004

- Rule 125 (SIZE3) found to be TRUE from Rule 35 & Rule 37

IF: ^^SHOAL SIZE^^ very small OR small

THEN: ^^PACKING DENSITY^^ very low AND low

NOTE:

(Knowledge-base #104): Packing density of saithe and cod schools was observed to increase as shoal size increased.

REFERENCE:

[ref#127] Partridge et al. 1980.

Calculation of Fuzzy Confidence for Rule 125:

IF confidence
 Condition 1 conf=0.140
THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
PACKING DENSITY	34	very low	0.000	0.010	0.001
		low	0.000	0.010	0.001

- Rule 131 (COHESION2) found to be TRUE from Rule 35 and Rule 37

IF: ^^SHOAL SIZE^^ medium

THEN: ^^SHOAL COHESION^^ medium

NOTE:

(Knowledge-base #110): Definition of cohesion: "A more cohesive school is defined as one in which there are fewer stragglers from the group, fewer aggressive interactions between individuals and which has a smaller dispersion of fish with the shoals (lower packing density). Individuals in such a shoal would appear to behave in a more unified manner (schooling)". Experiment with differences in hunger level and predation by bass on bluntnose minnows showed that shoal cohesiveness increased as both shoal size increased and in the presence of a predator, and decreased as hunger level increased.

REFERENCE:

[ref#99] Morgan 1988.

Calculation of Fuzzy Confidence for Rule 131:

IF confidence

Condition 1 confidence=0.200

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SHOAL COHESION	47	medium	0.000	0.030	0.006

End Nest 3

- Rule 137 (COHESION8) found to be TRUE from F9 and Rule 99

IF:

Abundance of aquatic predators frequent

THEN:

^^SHOAL COHESION^^ medium

NOTE:

(Knowledge-base #112): Definition of cohesion: "A more cohesive school is defined as one in which there are fewer stragglers from the group, fewer aggressive interactions between individuals and which has a smaller dispersion of fish with the shoals (lower packing density). Individuals in such a shoal would appear to behave in a more unified manner (schooling)". In the presence of a predator or under simulated predation risk shoals cohesiveness increases as predation threat increases.

REFERENCE:

[ref#99] Morgan 1988, [ref#209] Lima and Dill 1990, [ref#216] Krause and Godin 1994, [ref#218] Major 1978, [ref#237] Godin 1986 - (Andorfer 1980; Partridge 1982).

Calculation of Fuzzy Confidence for Rule 137:

IF confidence

Condition 1 conf=0.667

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SHOAL COHESION	47	medium	0.006	0.170	0.119

- Rule 138 (COHESION9) found to be TRUE from F9 and Rule 99

IF:

Abundance of aquatic predators common OR abundant

THEN:

^^SHOAL COHESION^^ high

NOTE:

(Knowledge-base #112): Definition of cohesion: "A more cohesive school is defined as one in which there are fewer stragglers from the group, fewer aggressive interactions between individuals and which has a smaller dispersion of fish with the shoals (lower packing density). Individuals in such a shoal would appear to behave in a more unified manner (schooling)". In the presence of a predator or under simulated predation risk shoals cohesiveness increases as predation threat increases.

REFERENCE:

[ref#99] Morgan 1988, [ref#209] Lima and Dill 1990, [ref#216] Krause and Godin 1994, [ref#218] Major 1978, [ref#237] Godin 1986 - (Andorfer 1980; Partridge 1982).

Calculation of Fuzzy Confidence for Rule 138:

IF confidence

Condition 1 conf=0.333

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SHOAL COHESION	47	high	0.000	0.170	0.057

End Nest 2

- Rule 104 found (FOODPWT3) to be TRUE from Rule 93

IF:

Feeding priority low

THEN:

[FZFOODAB] IS GIVEN THE VALUE [INFOOD][HIGHWT]*

NOTE:

Operational rule: at different stages in the adult life phase, "priority" rules are assigned to assert changes in motivational priorities to either feed, save energy, avoid predation risk or reproduce. The affect of these priorities on the structure and distribution of shoals is manifest by applying a weight factor (high, medium, low) that artificially changes certain attributes that correspond with the priority. For example - the effects of 'avoid risk priority' is manifest by changing the abundance of predators. This assumes that predation risk is proportional to the abundance of predators. The same method is applied to food abundance to reflect changes in feeding priority.

Calculation of Fuzzy Confidence for Rule 104:

IF confidence

Condition 1 conf=1.000

THEN added

Variable [FZFOODAB] set to 0.75 (conf=1)

Fact 10 derived from Rule 104

F10: Qualifier 5 had values set; Food abundance = almost non AND sparse

- Rule 105 (ENERGY P1) found to be TRUE from Rule 93

IF:

Energy saving priority high

THEN:

^^DYNAMIC TENDENCY^^ low

and ^^AVERAGE SWIMMING SPEED^^ OF ALL FISH IN A SHOAL low and ^^SHOAL MOVEMENTS^^ very restricted (fish holding)

NOTE:

Operational rule: at different stages in the adult life phase, "priority" rules are assigned to assert changes in motivational priorities to either feed, save energy, avoid predation risk or reproduce. The affect of these priorities on the structure and distribution of shoals is manifest by applying a weight factor (high, medium, low) that artificially changes certain attributes that correspond with the priority. An alternative method used here is to directly apply the effects on descriptors that influence energy saving strategies. A high weight is assigned to them ensuring their importance in the overall description of structure and distribution. Responses to energy saving priority are typically similar to those of avoid risk priority. Since these two priorities are typically both high at the same time the factors combine produce a more obvious effect.

Calculation of Fuzzy Confidence for Rule 105:

IF confidence

Condition 1 conf=1.000

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
DYNAMIC TENDENCY	36	low	0.000	0.900	0.900
AVERAGE SWIMMING SPEED	38	low	0.000	0.900	0.900
SHOAL MOVEMENTS	52	very restricted	0.000	0.900	0.900

Nest 2

- Rule 72 (SMOVE2) found to be TRUE from 105

IF:

^^SHOAL MOVEMENTS^^ very restricted (fish holding)

THEN:

^^SHOAL SIZE^^ large AND very large and ^^FISH DIRECTION^^ facing current

NOTE:

(Knowledge-base #73,69): For relatively non-mobile schools, the best strategy is perhaps to be in a large shoal, thus reducing risk of predation. For moving schools then perhaps the best strategy may be to travel in relatively small unit, thus allowing for rapid and co-ordinated response to any predation events. When fish are holding they always face into the prevailing current ('stem' the tide).

REFERENCE:

[31] Mackinson, [12] Armstrong, [14] Savard [22] Lenic, [21] Boroevich, [ref#208] DFO 1991

Calculation of Fuzzy Confidence for Rule 72:

IF confidence

Condition 1 conf=0.900

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SHOAL SIZE	45	large	0.070	0.100	0.154
		very large	0.000	0.100	0.090
FISH DIRECTION	48	facing current	0.000	0.140	0.126

- Rule 11 (SWSP1) found to be TRUE from Rule 105

IF:

^^AVERAGE SWIMMING SPEED^^ OF ALL FISH IN A SHOAL low

THEN:

^^PACKING DENSITY^^ low

NOTE:

(Knowledge-base #81): As swimming speed of individual decreases, the fish decrease their inter-fish distance, thereby reducing the overall packing density of the school.

REFERENCE:

[1] Misund, [ref#87] Pitcher and Partridge 1979 - (Partridge, B.L. 1981; Partridge et al. 1980), [ref#208] DFO 1991.

Calculation of Fuzzy Confidence for Rule 11:

IF confidence

Condition 1 conf=0.900

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
PACKING DENSITY	34	low	0.001	0.060	0.055

End Nest 2

- Rule 164 (HABITAT9) found to be TRUE from Rule 63

IF:

*SHOALS ^ASSOCIATED WITH SPECIFIC FEATURES^ (PHYSICAL/ OCEANOGRAPHIC)
passes with high flushing rate and inlets & bays*

THEN:

[PASSBAY] IS GIVEN THE VALUE 2

NOTE:

Operational rule for use in graphical display of shoals. If herring shoals are associated with a specific ocean/ topography/substrate feature a variable is switched from 0-'off' to 2-'on and associate'.

Calculation of Fuzzy Confidence for Rule 164:

IF confidence

Condition 1 conf=1.000

THEN added

Variable [PASSBAY] set to 2 (conf=1)

- Rule 123 (CATCHABIL3) found to be TRUE from Rule 108

IF:

^^STOCK FULFILMENT OF RANGE^^ intermediate

THEN:

^^CATCHABILITY (q)^^ medium

NOTE:

(Knowledge-base #102,103,86,92): Since stock size together with age structure determines the stock area range (knowledge-base #86,92) there is strong evidence that as stock size decreases so does the area over which they are distributed, even if there are no obvious environmental changes. Catchability "ratio of catch rate to biomass" (q), is a direct function of stock area which itself is density dependent on abundance. Thus, q increases as stock size decreases. Changes in catchability associated with abundance are captured here by rules relating catchability to stock area range.

REFERENCE:

[ref#3] Winters and Wheeler 1985, [ref#12] MacCall 1976, [ref#13] Csirke 1989, [ref#5] Pitcher 1995, [ref#14] Csirke 1988, [ref#18] Ulltang 1980, [ref#41] Paloheimo and Dickie 1964, [ref#42] Pope 1980, [ref#45] Sinclair et al. 1985, Radovich 1973, Saville and Bailey 1980.

Calculation of Fuzzy Confidence for Rule 123:

IF confidence

Condition 1 conf=0.172

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
CATCHABILITY (q)	58	medium	0.000	0.450	0.078

End Nest 1

- Rule 132 (COHESION3) found to be TRUE from Rule 35 & 72

IF:

^^SHOAL SIZE^^ large OR very large

THEN:

^^SHOAL COHESION^^ high

NOTE:

(Knowledge-base #110): Definition of cohesion: "A more cohesive school is defined as one in which there are fewer stragglers from the group, fewer aggressive interactions between individuals and which has a smaller dispersion of fish with the shoals (lower packing density). Individuals in such a shoal would appear to behave in a more unified manner (schooling)". Experiment with differences in hunger level and predation by bass on bluntnose minnows showed that shoal cohesiveness increased as both shoal size increased and in the presence of a predator, and decreased as hunger level increased.

REFERENCE:

[ref#99] Morgan 1988.

Calculation of Fuzzy Confidence for Rule 132:

IF confidence

Condition 1 confidence=0.230

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SHOAL COHESION	47	High	0.057	0.030	0.063

- Rule 8 (PD1) found to be TRUE from Rule 11 & 125

IF:

^^PACKING DENSITY^^ very low OR low

THEN:

^^RELATIVE EXTENT^^/ AREA OCCUPIED large

NOTE:

(Knowledge-base #12,80): For a given shoal size, the relative extent/area of the shoals will change depending on the packing density of fish within the shoal, which in turn is partly dependent on the average swimming speed on fish within the shoal.

REFERENCE:

[4] Melle, [31] Mackinson, [ref#72] Petitgas and Levenez 1996.

Calculation of Fuzzy Confidence for Rule 8:

IF confidence

Condition 1 confidence=0.057

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
RELATIVE EXTENT	35	large	0.000	0.900	0.051

- Rule 70 (SDEPTH1) found to be TRUE from Rule 6 & 35

IF:

SHOAL DEPTH surface OR bottom

THEN:

^^SHOAL SHAPE^^ horizontally elongated

NOTE:

(Knowledge-base #85): Typical shapes of herring schools are variable and depend on a number of factors other than simply their position in the water column. But, as a general view, schools tend to be close to spherical or ellipsoid in mid-water, and more horizontally elongated when close to the surface or bottom.

REFERENCE:

[3] Nøttestad, [31] Mackinson, [ref#10] Misund 1993, [ref#72] Petitgas and Levenez 1996, [ref#105] Misund and Aglen 1992, [ref#232] Breder 1967.

Calculation of Fuzzy Confidence for Rule 70:

IF confidence

Condition 1 confidence=0.393

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SHOAL SHAPE	44	Horizontally elongated	0.000	0.090	0.036

- Rule 126 (SIZE4) found to be TRUE from Rules 35,37,72

IF:

^^SHOAL SIZE^^ medium OR large OR very large

THEN:

^^PACKING DENSITY^^ medium

NOTE:

(Knowledge-base #104): Packing density of saithe and cod schools was observed to increase as shoal size increased.

REFERENCE:

[ref#127] Partridge et al. 1980.

Calculating Fuzzy Confidence for Rule 126:

IF confidence

Condition 1 conf=0.384

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
PACKING DENSITY	34	medium	0.362	0.010	0.365

- Rule 133 (COHESION4) found to be TRUE from Rule 104 & 119

IF:

Food abundance almost non OR sparse

THEN:

^^SHOAL COHESION^^ low

NOTE:

(Knowledge-base #111): Definition of cohesion: "A more cohesive school is defined as one in which there are fewer stragglers from the group, fewer aggressive interactions between individuals and which has a smaller dispersion of fish with the shoals (lower packing density). Individuals in such a shoal would appear to behave in a more unified manner (schooling)". Experiment with differences in hunger level and predation by bass on bluntnose minnows showed that shoal cohesiveness increased as both shoal size increased and in the presence of a predator, and decreased as hunger level increased.

REFERENCE:

[ref#99] Morgan 1988.

Calculation of Fuzzy Confidence for Rule 133:

IF confidence

Condition 1 conf=0.790

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SHOAL COHESION	47	low	0.004	0.030	0.028

- Rule 139 (ATTACK3) found to be TRUE from F4 and Rules 6,13,35,37

IF:

Time of day Day

and ^^INTERNAL DYNAMICS^^ schooling

and ^^SHOAL SIZE^^ very small OR small

THEN:

Attack rate of aquatic predators moderate

NOTE:

(Knowledge-base #113): Attack rate of predators depends on the vulnerability of the herring and on the strategy employed by the predators. Many visually oriented aquatic predators of herring are crepuscular in behaviour. They attack most of all during dawn and dusk period when changes in light condition may make the herring more visible and also changes in shoal structure (decrease packing density and move to shoaling/ feeding behaviour) make them particularly vulnerable. Shoal size plays an important part in vulnerability, small shoals being more vulnerable than large ones due to lower confusion and /or intimidation effects.

REFERENCE:

[19] Heglund, [13] Chalmers, [ref#128] Landeau and Terborgh 1986, [ref#99] Morgan 1988, [ref#121] Magurran 1990, [ref#167] Pitcher and Parrish 1993 -(Tremblay and Fitzgerald 1979; Parrish 1989; Foster and Treherne 1981; Morgan and Colgan 1987), [ref#171] Nøttestad and Axelsen 1997, [ref#218] Major 1978.

Calculation of Fuzzy Confidence for Rule 139:

IF confidence

Condition 1 conf=1.000

Condition 2 conf=0.909

Condition 3 conf=0.140

Total IF conf=0.127

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
Attack rate of aquatic predators	13	moderate	0.000	0.480	0.061

- Rule 38 (ATTACK4) found to be TRUE from F4 and Rules 6,13,35,37,72

IF:

Time of day Day

and ^INTERNAL DYNAMICS^ schooling

and ^SHOAL SIZE^ medium OR large OR very large

THEN:

Attack rate of aquatic predators low

NOTE:

(Knowledge-base #113): Very large schools do not suffer high attack rates from predators even at times when the herring may appear particularly vulnerable. This may be due to either intimidation of the predator from the sheer size of the schools or perhaps from the confusion effects of such a large number of fish. Large schools are also known to have a broader repertoire of anti-predator tactics than smaller schools.

REFERENCE:

[19] Heglund, [13] Chalmers, [ref#128] Landeau and Terborgh 1986, [ref#99] Morgan 1988, [ref#121] Magurran 1990, [ref#167] Pitcher and Parrish 1993 -(Tremblay and Fitzgerald 1979; Parrish 1989; Foster and Treherne 1981; Morgan and Colgan 1987), [ref#171] Nøttestad and Axelsen 1997, [ref#218] Major 1978.

Calculation of Fuzzy Confidence for Rule 38:

IF confidence

Condition 1 conf=1.000

Condition 2 conf=0.909

Condition 3 conf=0.384

Total IF conf=0.349

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
Attack rate of aquatic predators	13	low	0.000	0.480	0.168

- Rule 9 (PD2) found to be TRUE from Rules 6,13,35,37,126

IF:

^^PACKING DENSITY^^ medium

THEN:

^^RELATIVE EXTENT^^/ AREA OCCUPIED medium

NOTE:

(Knowledge-base #12,80): For a given shoal size, the relative extent/area of the shoals will change depending on the packing density of fish within the shoal, which in turn is partly dependent on the average swimming speed on fish within the shoal.

REFERENCE:

[4] Melle, [31] Mackinson, [ref#72] Petitgas and Levenez 1996.

Calculation of Fuzzy Confidence for Rule 9:

IF confidence

Condition 1 confidence=0.365

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
RELATIVE EXTENT	35	medium	0.000	0.900	0.328

No more facts can be derived so system asks question for next qualifier (Fig 5.9)

BIOSPHERICAL FACTORS

Stage of the tide:

high slack

low slack

ebb

flood

Strength of water current (knots)

use the slide bar to indicate the approximate current strength

0

10

2

3

4

5

6

7

8




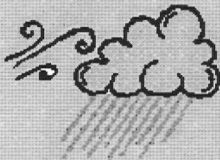

9

Water depth (meters)

Please enter the approximate water depth in meters (note: 1 fathom= 2 meters)

150

Weather conditions

Use mouse to double click on picture that best describes weather

EXIT

Known info.

HELP

Figure 5.9 Input screen for biophysical factors.

Facts derived from input

- F11: Qualifier 21 choices set; State of tide = ebb (Conf=1)
- F12: Variable [CURRSTREN] set to 2 (Conf=1); set qualifier 20: Strength of current = not strong
- F13: Variable [WDEPTH] set to 150 (Conf=1); set qualifier 17: Water depth = mid-range AND deep
- F14: Qualifier 57 choices set; Choose description that best describes the weather = perfect calm and sunny (conf=1)

Rules derived from Facts

- Rule 114 (WEATHER2) found to be TRUE from F12

IF:

Choose description that best describes the weather perfect calm and sunny

THEN:

[WEATHER] IS GIVEN THE VALUE 5

NOTE:

Operational rule: using the graphics selected by the users this rule assigns a value to a continuous variable weather that is associated with a fuzzy variable. The method is used so that the user is offered a simple friendly type of question.

Calculation of Fuzzy Confidence for Rule 114:

IF confidence

Condition 1 conf=1.000

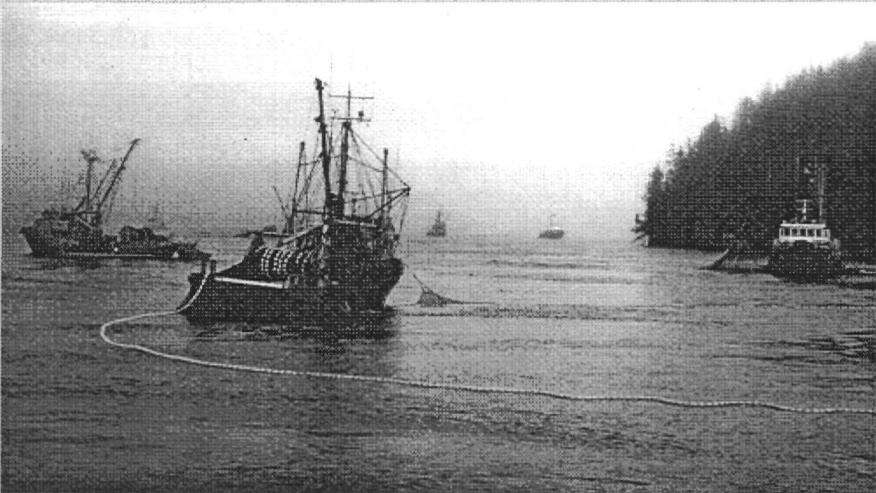
THEN added

Variable [WEATHER] set to 5 (conf=1)

Qualifier 25 Value(s) set; Weather conditions = good - fine and calm

No more qualifiers can be derived, system asks next question (Fig 5.10)

AVOIDANCE TO VESSELS



use the slide bar to indicate the degree to which fish are displaying avoidance reactions to vessels

NON
A LITTLE
SOME
SIGNIFICANT
LOADS

EXIT
Known info.
HELP
OK, all done

Figure 5.10 Vessel avoidance input screen.

Facts derived from input

F15: Variable [AVOID] set to 1; set qualifier 29: Fish showing general avoidance response = weak (Conf=1)

No more qualifiers can be derived, system asks next question (Fig 5.11)

Size composition of fish in shoals

select ONLY ONE value

- ☐ mostly small fish (<17cm)
- ☐ mostly large fish (>17cm)
- ☒ mixture of small and large fish

EXIT
Known info
Why?
Help
OK, done

Figure 5.11 Fish size composition input screen.

Facts derived from input

F16: Qualifier 46 set; SIZE COMPOSITION OF FISH IN SHOAL = mixture of small and large fish


No more qualifiers can be derived, system asks next question (Fig 5.12)

TYPICAL TOPOGRAPHY AND BOTTOM FEATURES
check the boxes to indicate which bottom type is most typical of the area you are considering

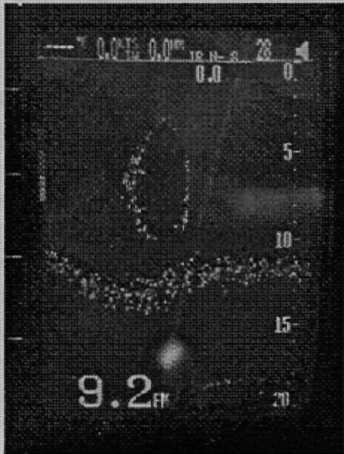
☐ Steep sided deep channels

☐ Hard bottom with rock outcroppings

☒ Soft bottom with surface irregularities



example of rocky bottom forming spikes and reef structures



example of soft bottom substrate with surface irregularity. Note changes in depth are generally gradual when compared to rock bottoms

Figure 5.12 Physical topography/ substrate input screen.

Facts derived from input

F17: Qualifier 22 choices set; Typical topography and substrate features are = soft bottom with surface irregularities (dips and trenches) (Conf=1)

Rules derived from facts

- Rule 62 (ASSOC2) found to be TRUE from F2, F4, F17

IF:

*Life phase pre-spawning OR overwintering
and Time of day Day*

and Typical topography and substrate features are: soft bottom with surface irregularities (dips and trenches)

THEN:

*SHOALS ^^ASSOCIATED WITH SPECIFIC FEATURES^^ (PHYSICAL/ OCEANOGRAPHIC)
soft bottom with irregularities in seabed floor*

NOTE:

(Knowledge-base #70): During periods where herring are 'holding' in specific areas (e.g. early pre-spawners), they form strong association with particular topographical and substrate features. Although shoal may be found in areas with rock outcroppings, it is generally only on soft substrates such as mud and sand that herring will lie on the bottom during the day. Bays and inlets commonly

have mud bottoms, so selection of particular substrate type may in part explain the tendency for some shoals to be found associated with bays.

REFERENCE:

[7] McCarter, [29] Wilson, [16] Redford, [17] Malatestinic, [18] Reid, [11] Webb, [12] Armstrong, [19] Heglund, [13] Chalmers, [15] Thomas, [22] Lenic, [21] Boroevich, [24] Pierce, [23] Carr, [28] Hunt, [31] Mackinson, [ref#101] Maravelias and Haralabous 1995, [ref#198] Slotte 1998, [ref#208] DFO 1991, [ref#231] Blaxter and Holliday 1969 - (Jakobsson 1961), Reid 1995, Maravelias 1997, Maravelias and Reid 1995, Maravelias and Reid 1997, Maravelias et al. 1997, Reid et al. 1993

Calculation of Fuzzy Confidence for Rule 62:

IF confidence

Condition 1 conf=1.000

Condition 2 conf=1.000

Condition 3 conf=1.000

Total IF conf=1.000

THEN added...

Qualifier	Q#	Value	Current conf.	Assigned conf.	New conf.
SHOALS ASSOCIATED WITH SPECIFIC FEATURES	43	soft bottom with irregularities in seabed floor	0.000	1.000	1.000

Rules derived from rules

- Rule 162 (HABITAT7) found to be TRUE from Rule 63

IF:

SHOALS ^ASSOCIATED WITH SPECIFIC FEATURES^ (PHYSICAL/ OCEANOGRAPHIC)
soft bottom with irregularities in seabed floor

THEN:

[SOFTBOT] IS GIVEN THE VALUE 2

NOTE:

Operational rule for use in graphical display of shoals. If herring shoals are associated with a specific ocean/ topography/substrate feature a variable is switched from 0-'off' to 2-'on and associate'.

Calculation of Fuzzy Confidence for Rule 162:

IF confidence

Condition 1 conf=1.000

THEN added

Variable [SOFTBOT] set to 2 (Conf=1)

- Rule 157 (HABITAT2) found to be TRUE from Rule 62 & 63

IF:

SHOALS ^ASSOCIATED WITH SPECIFIC FEATURES^ (PHYSICAL/ OCEANOGRAPHIC)
NOT rock pinnacles/ reef structure

THEN:

[ROCKREEF] IS GIVEN THE VALUE 0

NOTE:

Operational rule for use in graphical display of shoals. If herring shoals are associated with a specific ocean/ topography/substrate feature a variable is switched from 0-'off' to 2-'on and associate'.

Calculation of Fuzzy Confidence for Rule 157:

IF confidence

Condition 1 conf=1.000

THEN added

Variable [ROCKREEF] set to 0 (Conf=1)

- Rule 159 (HABITAT4) found to be TRUE from Rule 62 & 63

IF:

*SHOALS ^ASSOCIATED WITH SPECIFIC FEATURES^ (PHYSICAL/ OCEANOGRAPHIC)
NOT frontal zone*

THEN:

[FRONTAL] IS GIVEN THE VALUE 0

NOTE:

Operational rule for use in graphical display of shoals. If herring shoals are associated with a specific ocean/ topography/substrate feature a variable is switched from 0-'off' to 2-'on and associate'.

Calculation of Fuzzy Confidence for Rule 159:

IF confidence

Condition 1 conf=1.000

THEN added

Variable [FRONTAL] set to 0 (Conf=1)

- Rule 161(HABITAT6) found to be TRUE from Rule 62 & 63

IF:

*SHOALS ^ASSOCIATED WITH SPECIFIC FEATURES^ (PHYSICAL/ OCEANOGRAPHIC)
NOT bluffs of steep sided channels*

THEN:

[STEEPBLUFF] IS GIVEN THE VALUE 0

NOTE:

Operational rule for use in graphical display of shoals. If herring shoals are associated with a specific ocean/ topography/substrate feature a variable is switched from 0-'off' to 2-'on and associate'.

Calculation of Fuzzy Confidence for Rule 161:

IF confidence

Condition 1 conf=1.000

THEN added

Variable [STEEPBLUFF] set to 0 (Conf=1)

- Rule 167 (HABITAT12) found to be TRUE from Rule 62 & 63

IF:

*SHOALS ^ASSOCIATED WITH SPECIFIC FEATURES^ (PHYSICAL/ OCEANOGRAPHIC)
NOT hard bottom with rock outcroppings*

THEN:

[HARDBOT] IS GIVEN THE VALUE 0

NOTE:

Operational rule for use in graphical display of shoals. If herring shoals are associated with a specific ocean/ topography/substrate feature a variable is switched from 0-'off' to 2-'on and associate'.

Calculation of Fuzzy Confidence for Rule 167:

IF confidence

Condition 1 conf=1.000

THEN added

Variable [HARDBOT] set to 0 (Conf=1)

- Rule 180 (HABITAT18) found to be TRUE from Rule 62 & 63

IF:

SHOALS ^ASSOCIATED WITH SPECIFIC FEATURES^ (PHYSICAL/ OCEANOGRAPHIC)

passes with high flushing rate and inlets & bays

and SHOALS ^ASSOCIATED WITH SPECIFIC FEATURES^ (PHYSICAL/ OCEANOGRAPHIC)

soft bottom with irregularities in seabed floor

THEN:

[PASSBAY] IS GIVEN THE VALUE 2

and [SOFTBOT] IS GIVEN THE VALUE 2

NOTE:

Operational rule for use in graphical display of shoals. If herring shoals are associated with a specific ocean/ topography/substrate feature a variable is switched from 0-'off' to 2-'on and associate'.

Calculation of Fuzzy Confidence for Rule 180:

IF confidence

Condition 1 conf=1.000

Condition 2 conf=1.000

THEN added

Variable [PASSBAY] set to 2 (conf=1)

Variable [SOFTBOT] set to 2 (conf=1)

No more facts can be derived and all rules have been tested; CLUPEX displays the output screen with fuzzy predictions (Fig 5.13). In addition to hypertext (words highlighted in blue, accessed by double clicking) explanations for each descriptor, the results screen provides access to the explanation facility allowing a user to query as to how certain conclusion were drawn and predictions made. To do this, the mouse is used to select an item on the results screen, and then the "How" button is pressed; rules relating to the item that were found to be true are displayed in sequence (Fig 5.14). For example, asking how the fuzzy prediction 'shoal size = *small, medium, large and very large*', was derived, it is found that Rules 35,37,72 were all found to be true. Notes and references associated with each rule can be examined at this stage. Additionally, by selecting the IF part of the rule, and pressing the "Source" button the user can ask how the rule was found to be true.

At the end of the list of results, de-fuzzified values are given for each quantitative descriptor. Similarly, the user may ask how these were derived and the system displays the de-fuzzification

calculations (Fig 5.15). Finally, when the user has finished with the explanation facility and presses "Done" on the results screen, summary tables of both quantitative and qualitative results are given (Fig 5.16).

In summary, Table 5.2 shows the facts and rules used in deriving predictions for each descriptor of shoal structure, dynamics and distribution in the example of overwintering Pacific herring.

Results

Confidence	
	PACKING DENSITY very low (Conf=.004) AND low (Conf=.114) AND medium (Conf=.598) AND high (Conf=.123)
	RELATIVE EXTENT/ AREA OCCUPIED small (Conf=.161) AND medium (Conf=.69) AND large (Conf=.106)
	DYNAMIC TENDENCY low (Conf=.99) AND medium (Conf=.19) AND high (Conf=.097)
	INTERNAL DYNAMICS
	AVERAGE SWIMMING low (Conf=.99) AND
	EASE OF CAPTURING
	SHOAL DEPTH deep
	SEGREGATION OF S there is no result for
	SHOALS ASSOCIATE (PHYSICAL/ OCEAN) irregularities in seal high flushing rate at
	SHOAL SHAPE horizontal spheroid (Conf=.085) AND layer (Conf=.085)
	SHOAL SIZE small (Conf=.26) AND medium (Conf=.36) AND large (Conf=.291) AND very large (Conf=.18)

Double click on an item to see the rule(s) used

ReSolver

Size/age class segregation

Comments on the occurrence that the shoal is segregated based on size class of fish. Since herring typically swim with fish of the same size, size sorting of fish within a shoal may occur, particularly during vertical migration. When small and large fish are mixed within one shoal, the difference in dynamics related to size of the fish can result in a very heterogeneous shoal structure, including regions of varying densities. High density patches are thought to be smaller fish since smaller fish assume a tighter packing density.

Done

Figure 5.13 Results screen with hypertext and explanation of fuzzy predictions.

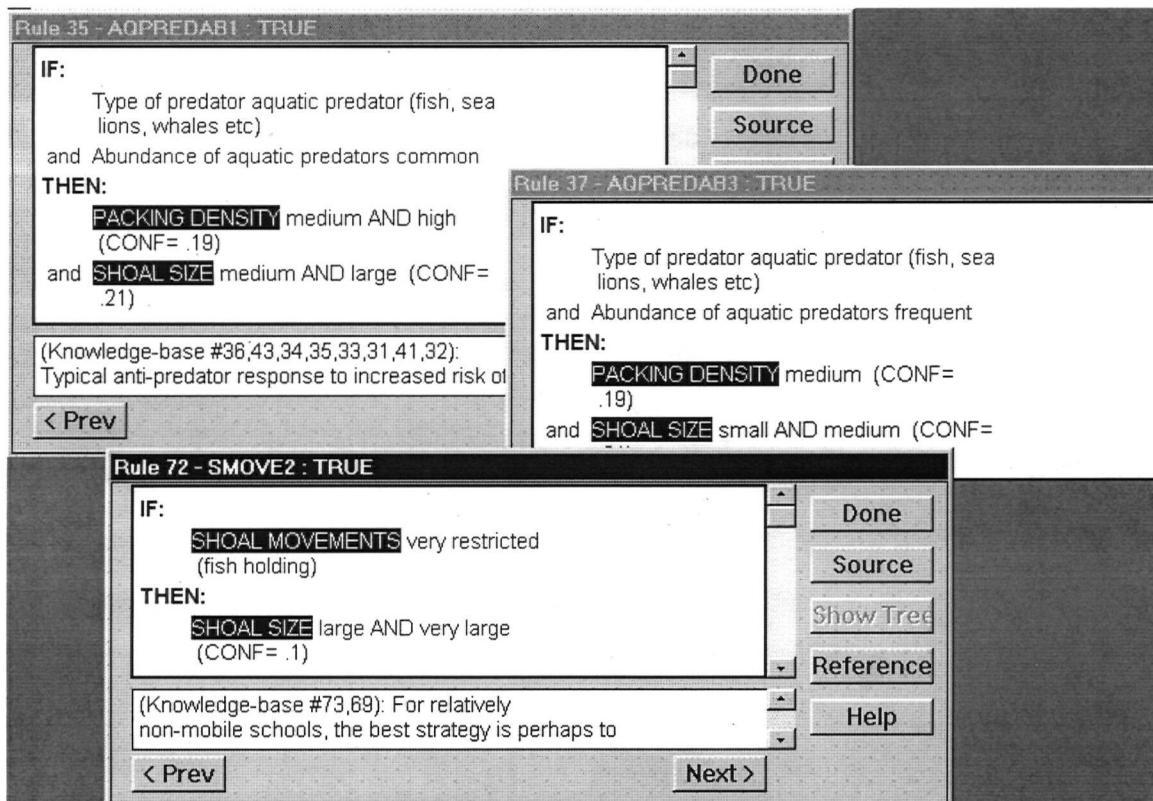


Figure 5.14 Rules used in predicting shoal size for overwintering Pacific herring example.

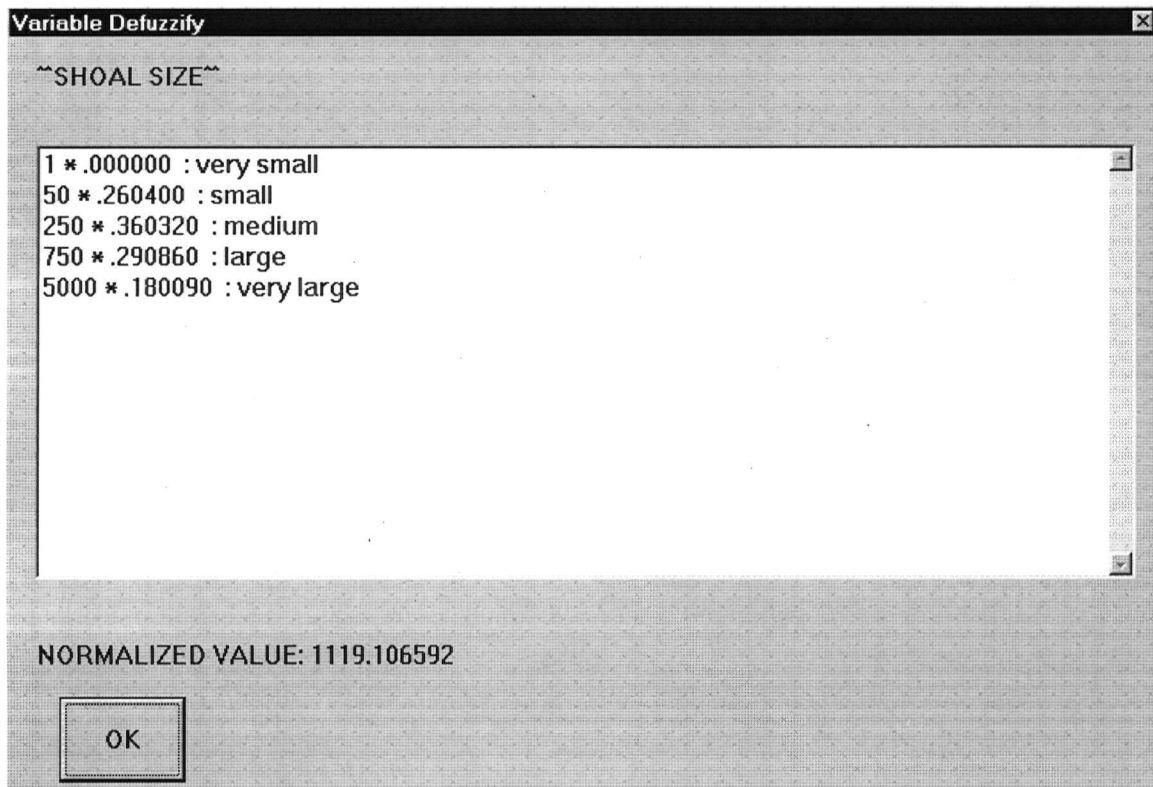


Figure 5.15 De-fuzzification calculation for quantitative prediction of shoal size for overwintering Pacific herring example.

Quantitative descriptors of shoal Structure, Dynamics & Distribution

	Low	Middle	High
Shoal size (t)	283	1119	4646
Packing density (fish per m ³)	1.5	5.2	14.7
mean NND (km)	0.2	0.6	1.3
mean av. ISD (km)	38	63	100
Rel. depth (%)	75	88	98
Speed (m per sec)	0.07	0.27	0.54
Dynamic tendency (behavioural events per hour)	3	7	11
Ease of capture (% successful sets)	10	25	40

Figure 5.16 Summary output screen of quantitative predictions.

Table 5.2 Summary table of rules and facts used predicting structure, dynamics and distribution of overwintering Pacific herring shoals.

Qualifier	Value	Final CF	Facts (Input)	Derived using rules
Location	Pacific ocean	1	F1	
Life phase	overwintering	1	F2	
Importance of time of day	important	1	F3	
Time of day	Day	1	F4	
[inputstock]	20,000	1	F5	
AGE STRUCTURE OF STOCK	mature	0.75	F6: set by [ageclass=8]	
RELATIVE STOCK SIZE	medium	1	F7	
Predator species	Fish	1	F8	
Abundance of aquatic predators	frequent	0.667	F9: set by [FZPREDDA B=6]	R 99
Food abundance	AND common almost non	0.333 0.7	F10: set by [FZFOOD=0.75]	R 104, 119
State of tide	AND sparse ebb	0.3 1	F11	
Strength of current	not strong	0.992	F12: set by [currstren=2]	

Water depth	mid-range	0.5	F13:set by [wdepth =150] F14	
Choose description that best describes the weather	perfect calm and sunny	1		
Weather conditions	good - fine and calm	1	Set by [weather=5]	R 114
Fish showing general avoidance response	weak	0.971	F 15: set by [avoid =1]	
SIZE COMPOSITION OF FISH IN SHOAL	mixture of small and large fish	1	F16	
Typical topography and substrate features are	soft bottom with surface irregularities (dips and trenches)	1	F17	
Species	Pacific herring	1		R 128
Feeding status	barely feeding	1		R 93
	AND sea lions and seals	1		
Feeding priority	low	1		R 93
Avoid predation risk priority	high	1		R 93
Reproduce priority	medium	1		R 93
Energy saving priority	high	1		R 93
Type of predator	aquatic predator	1		R 33
Attack rate of aquatic predators	low	0.168		R 38
	AND moderate	0.061		R139
Pre-spawning maturation stage	low importance	1		R96
	AND deep	0.5		
PACKING DENSITY	very low	0.001		R 125
	AND low	0.055		R 11, 125
	AND medium	0.365		R 6,13,35,37,126
	AND high	0.063		R 35
RELATIVE EXTENT / AREA OCCUPIED	small	0.057		R 10
	AND medium	0.328		R 9
	AND large	0.051		R 8
DYNAMIC TENDENCY	low	0.9		R 105
	AND medium	0.1		R 37
	AND high	0.05		R 35
INTERNAL DYNAMICS	schooling	0.909		R 6,13,35,37

AVERAGE SWIMMING SPEED OF ALL FISH IN A SHOAL	low	0.9	R 105
EASE OF CAPTURING A SCHOOL	AND high low	0.01 0.25	R 35 R 6
SHOAL DEPTH	deep	0.393	R 6,35
	AND bottom	0.393	R 6,35
SEGREGATION OF SIZE CLASSES / AGE CLASSES	there is no result for this descriptor	1	R 146
SHOALS ASSOCIATED WITH SPECIFIC FEATURES (PHYSICAL/ OCEANOGRAPHIC)	soft bottom with irregularities in seabed floor	1	R 62
	AND passes with high flushing rate and inlets & bays	1	R 63
SHOAL SHAPE	horizontally elongated	0.036	R 13,70
	AND spheroid	0.043	R 35
	AND layer	0.043	R 35
SHOAL SIZE	small	0.14	R 37
	AND medium	0.2	R 35, 37
	AND large	0.154	R 35, 72
	AND very large	0.09	R 72
SHOAL COHESION	low	0.028	R 130, 133
	AND medium	0.119	R 131, 137
	AND high	0.063	R 132, 138
FISH DIRECTION NEAREST NEIGHBOUR DISTANCE	facing current	0.126	R 72
	low	0.013	R 35
	AND medium	0.185	R 6,37,148
	AND high	0.08	R 6
Mean INTER-SCHOOL distance	medium	0.15	R 6
	AND high	0.15	R 6
LOCATION SHIFT	there is no result for this descriptor	1	R 145
SHOAL MOVEMENTS	very restricted (fish holding)	1	R 105

STOCK FULFILMENT OF RANGE	intermediate	0.173	R 108
STOCK DISTRIBUTION EXTENT	there is no result for this descriptor	1	R 145
CATCHABILITY (q)	medium	0.078	R 123
[ROCKREEF]	0	1	R 157
[FRONTAL]	0	1	R 159
[STEEPBLUFF]	0	1	R 161
[HARDBOT]	0	1	R 167
[SOFTBOT]	2	1	R 162, 180
[PASSBAY]	2	1	R 164, 180
[SPAWN SUB]	0	1	R 169

Example 2: Ocean feeding Norwegian spring spawning herring

In this example, several differences emphasise the 'intelligent' nature of CLUPEX. On initiation, the configuration file ensures that the user is prompted first to specify the location of choice and secondly to input general characteristics (same input screens as Fig 5.5 & 5.6). However, the facts input using these screens results in different rules being found to be true. In response to the new information from these rules, different questions are asked of the system. Only those pertinent to the specified conditions are required; in the ocean feeding scenario, food and feeding attributes are a priority and are asked of the user (Fig 5.17).

ReSolver

FOOD AND FEEDING

Food abundance: use the slide bar to indicate the relative abundance of food on a scale 0-10

0 1 2 3 4 5 6 7 8 9 10

Food size

- ☒ Small
- ☒ Medium
- ☒ Large

Features that food patches are associated with

- rock pinnacles/ reef structures
- ocean front zone (e.g. temperature, cu
- not sure

Food depth distribution

- shallow
- mid-range
- deep
- very deep

Distance between food patches

low

EXIT Known info. HELP OK, all done

Figure 5.17 Input screen for food and feeding attributes asked during ocean feeding scenario.

Following this the user is asked to specify predator species and their abundance (same as Figs 5.7 & 5.8). Since CLUPEX cannot determine the fish direction from current facts, it is asked (Fig 5.18). If the user is unable to answer the question, an option 'not sure' is presented.

Direction of fish with respect to current

select ONLY ONE value

☒ facing in to current

☐ positioned with current behind

☐ not sure

EXIT Known info Why? Help OK, done

Figure 5.18 Fish direction screen asked of user.

The user is next requested to specify biophysical attributes (same as Fig 5.9) and then whether or not herring are apparently competing with other species for food resources (such as in mixed schools of herring and blue whiting) (Fig 5.19).

Competition with other species

select ONLY ONE value

☐ active competition

☒ no competition

☐ not sure

EXIT Known info Why? Help OK, done

Figure 5.19 Competition for other species input screen.

The next question is on vessel avoidance (same as Fig 5.10), followed by a question regarding the distribution of birds (Fig 5.20). Since it might not be immediately obvious as to why such a question is being asked, the user can ask 'Why?' via the question menu (Fig 5.20). Rule 48 is presented showing it has not been tested; elements of the IF part typed in black have previously been found to be true and it possible to find out how by selecting an item and pressing the "Source" button.

Distribution of birds
select ONLY ONE value

- ☐ scattered
- ☐ concentrated patches
- ☒ not sure

EXIT Known info Why?

Rule 48 - BDIST2 : NOT TESTED

IF:
Time of day NOT Night
and Predator species small birds OR large birds
and Distribution of birds concentrated patches

THEN:
PACKING DENSITY medium AND high (CONF= .04)
and SHOAL SIZE medium AND large (CONF= .04)

(Knowledge-base #37): Birds tend to make strong associations with schools

< Prev Next >

Done
Source
Reference
Help

Figure 5.20 Input screen for bird distribution and query of 'Why?' the question is being asked.

Finally, the user is asked to specify the local water temperature regime at the location being considered (Fig 5.21). Similarly, the user may ask 'Why?' the question is being asked.

Water temperature regime at location
select ONLY ONE value

- ☒ at a cold threshold (minimum temp. tolerance)
- ☐ warmer than normal
- ☐ cooler than normal
- ☐ normal
- ☐ not sure

EXIT Known info Why? Help OK, done

Figure 5.21 Input screen for water temperature regime.

In the ocean feeding Norwegian spring spawning herring scenario, there are distinct differences in operation of CLUPEX. First, in this example, the user is not required to input information on the size composition of fish in shoals (see Fig 5.4) or the physical topography/ substrate (see Fig 5.5). Second, more questions are asked of the user, and consequently 22 facts are required as

input (in contrast to 17 for example 1) for the system to make its predictions. Third, 70% of rules found to be true were specific to this scenario; only 19 of the fired rules were common to both examples (Table 5.3).

The percentage of rules found to be true (out of total 186 tested) and therefore used in predictions, was 24% for overwintering Pacific herring and 33% for ocean feeding Norwegian spring spawning herring.

Table 5.3 Summary table of rules and facts used in predicting structure, dynamics and distribution of ocean feeding Norwegian spring spawning herring shoals. Rules and qualifiers highlighted in bold are particular to this run and do not occur in example 1.

Qualifier	Value	Final CF	Facts (Input)	Derived using rules
Location	Norwegian Sea	1	F1	
Life phase	ocean feeding	1	F2	
Importance of time of day (special case of time in which to know answer)	not important	1	F3	
Time of day	Day	1		R97
[inputstock]	5,000,000	1	F4	
AGE STRUCTURE OF STOCK	mature	1	F5: set by [AGECLASS =12]	
RELATIVE STOCK SIZE	large	1	F6	
	AND very large	1		
Food abundance	sparse	0.68	F7: set by [FZFOODA B=3.3]	
	AND moderate	0.32		
Size of food	small	1	F8	
	AND medium	1		
	AND large	1		
Food depth distribution	shallow	1	F9	
	AND mid- range	1		
Food patches associated with specific ocean features	ocean front zone (e.g. temperature, currents, upwelling)	1	F10	
Distance between food patches	low	1	F11	
Predator species	Fish AND sea	1	F12	

	lions and seals			
	AND small			
	birds AND			
	large birds			
Abundance of aquatic predators	frequent	1	F13: set by [FZPREDAB =5]	
FISH DIRECTION	facing current	1	F14	
State of tide	ebb	1	F15	
Strength of current	not strong	0.992	F16: set by [currstren=2]	
Water depth	very deep	1	F17: set by [wdepth=100 0]	
Choose description that best describes the weather	cloud and sun, maybe light showers	1	F18	
Weather conditions	In-between	1	Set by [weather=4]	
	AND good - fine and calm	0.5		
Competition from other species	no competition	1	F19	
Fish showing general avoidance response	weak	0.971	F20: set by [avoid=1]	
Distribution of birds	not sure	1	F21	
Water temperature regime at location	at a cold threshold (minimum temperature tolerance)	1	F22	
Species	Atlantic herring (Clupea harengus)	1		R127
Feeding status	feeding	1		R91
Hunger status	low	0.32		R43
	AND high	0.68		R42
Feeding mode	visual selection	0.46		R32
Feeding priority	high	1		R91
Avoid predation risk priority	medium	1		R91
Reproduce priority	low	1		R91
Energy saving priority	low	1		R91
Type of predator	aquatic predator	1		R33
	AND bird predator	1		R34

Attack rate of aquatic predators	low	0.1	R38
	AND moderate	0.217	R139, 141
	AND high	0.129	R140
Pre-spawning maturation stage	low importance	1	R96
PACKING DENSITY	very low	0.078	R19, 125
	AND low	0.159	R11,12,19,125,177
			7
	AND medium	0.425	R6,12,37,126,177
RELATIVE EXTENT / AREA OCCUPIED	medium	0.382	R9
	AND large	0.202	R8
DYNAMIC TENDENCY	low	0.04	R153
	AND medium	0.929	R14,18,37,107
	AND high	0.005	R14
INTERNAL DYNAMICS	schooling	0.913	R6,12,37
	AND shoaling	0.9	R18
AVERAGE SWIMMING SPEED OF ALL FISH IN A SHOAL	low	0.014	R21
	AND medium	0.9	R107
EASE OF CAPTURING A SCHOOL	low	0.25	R6
SHOAL DEPTH	shallow	0.05	R25
	AND mid-range	0.5	R83
	AND deep	0.37	R6
	AND bottom	0.37	R6
DISTANCE TO SHORE	far away	1	R142
SEGREGATION OF SIZE CLASSES / AGE CLASSES	there is no result for this descriptor	1	R186
SHOALS ASSOCIATED WITH SPECIFIC FEATURES (PHYSICAL/ OCEANOGRAPHIC)	frontal zone	1	R154
SHOAL SHAPE	horizontally elongated	0.07	R15,70
	AND spheroid	0.045	R71
	AND amorphous	0.038	R15
SHOAL SIZE	very small	0.048	R19
	AND small	0.264	R19,37,177

SIZE COMPOSITION OF FISH IN SHOAL	AND medium mixture of small and large fish	0.228 0.1	R37,177 R46
SHOAL COHESION	low	0.029	R130,133
NEAREST NEIGHBOUR DISTANCE	AND medium low	0.184 0.099	R131,134,137 R82,149
Mean INTER-SCHOOL distance	AND medium AND high low	0.21 0.286 0.166	R6,23,37 R6,22 R28,79
LOCATION SHIFT	AND medium AND high unlikely to occur	0.175 0.15 0.328	R6,79 R6 R41
SHOAL MOVEMENTS	moderate	0.9	R107
STOCK FULFILMENT OF RANGE	fulfilled	0.23	R110
STOCK DISTRIBUTION EXTENT	AND maximum capacity at limit	0.23 0.21	R112 R80
CATCHABILITY (q)	low	0.104	R151
	AND low- medium	0.104	R124
[ROCKREEF]	0	1	R157
[FRONTAL]	2	1	R158
[STEEPBLUFF]	0	1	R161
[HARDBOT]	0	1	R167
[SOFTBOT]	0	1	R163
[PASSBAY]	0	1	R165
[SPAWNSUB]	0	1	R169

5.4 Results and sensitivity analysis

Qualitative and quantitative output formats are used in predicting structure, dynamics and meso-scale distribution of herring shoals. Model predictions are evaluated here in 2 ways:

1. Examination of general predictions for three hypothetical scenarios:
 - (i) diurnal changes in overwintering Pacific herring;
 - (ii) differences over a range of predator and food abundance's for daytime ocean feeding Norwegian spring spawning;
 - (iii) complete one year cycle of seasonal changes in Pacific herring.
2. Comparison of model predictions with new 'test data' - data for Pre-spawning Pacific herring from the Central Coast fishing region of British Columbia, Canada. This data was not utilised in development of the system.

Details of input parameters used in the three scenarios are provided in Appendix 5.4

General predictions

(i) Diurnal changes in overwintering Pacific herring

Figures 5.22 (a-e) and Table 5.4 display the main predicted quantitative and qualitative diurnal changes. For brevity, descriptors that do not show any change are omitted from the results. In addition, Figures 5.22 (f-h) show how changes in state of tide and moonlight are predicted to alter the 'typical' diurnal pattern. Some general model predictions for the overwintering period considered in this scenario are that shoals are typically found located in coastal waters in areas with high flushing or circulation properties such as passes, bays and inlets. They display very restricted movement 'holding' and as a consequence the fish are assumed to be positioned facing in to the current. Shoal size is large, averaging 736t with a range from 200 – 2774t. To accompany Fig. 5.22 and Table 5.4, a summary of the diurnal changes predicted by CLUPEX is provided below.

Daytime shoals are located deep in the water column, forming discrete, variously shaped schools closely associated with features of the seabed. Packing density is predicted to range from approximately 1.5 to 14 fish per m^3 , with an average around 5 fish per m^3 . Note that the frequent occurrence of predators (assumed during input, but not obvious from results) has an important influence on packing density. At dusk, shoals break their association with the seabed and rise in the water column. At this time, shoals comprised of a mixture of small and large fish may exhibit a vertical separation. Average distance between nearest neighbour shoals (mean NND – mean nearest neighbour distance) and between all shoals (mean \overline{ISD} – mean of the average distance from an individual shoal to all other shoals) declines, resulting in an overall distribution that is

still aggregated (shoal clusters occur) but less patchy overall. Packing density steadily declines, and during this vulnerable period, both predators and seine fishers enjoy high success. By night time, shoals are distributed as a layer in the upper quarter of the water column with density as low as 0.3 fish per m^3 . The area over which the fish are distributed is further reduced (mean \overline{ISD}). During the night, a horizontal migration may occur, some herring (assumed to be the smaller ones) moving close to the shoreline. In the dark of night, the diffuse layer of fish reduces the ease of capture for the seine fisher and visually oriented fish predators. The onset of dawn sees the re-formation of schooling habit and re-aggregation of school clusters and dispersion across a wider area. The discrete more densely packed schools, still relatively high in the water column form an easy target for the seine fisher. This period of high contrast, like dusk, is also a period of high attack rate by aquatic predators.

Two important modifications to the predicted 'typical' pattern summarised above are forecast by CLUPEX. Firstly, in relatively shallow waters (<200m) during day time when the tide is at high or low slack, shoals are found to weaken their association with the seafloor and rise higher in the water column (Fig. 5.22f). Secondly, during moon bright nights, the rise in the water column and reduction in packing density occurs faster at dusk, although by night, shoals are generally found deeper than normal (Fig. 5.22g & h).

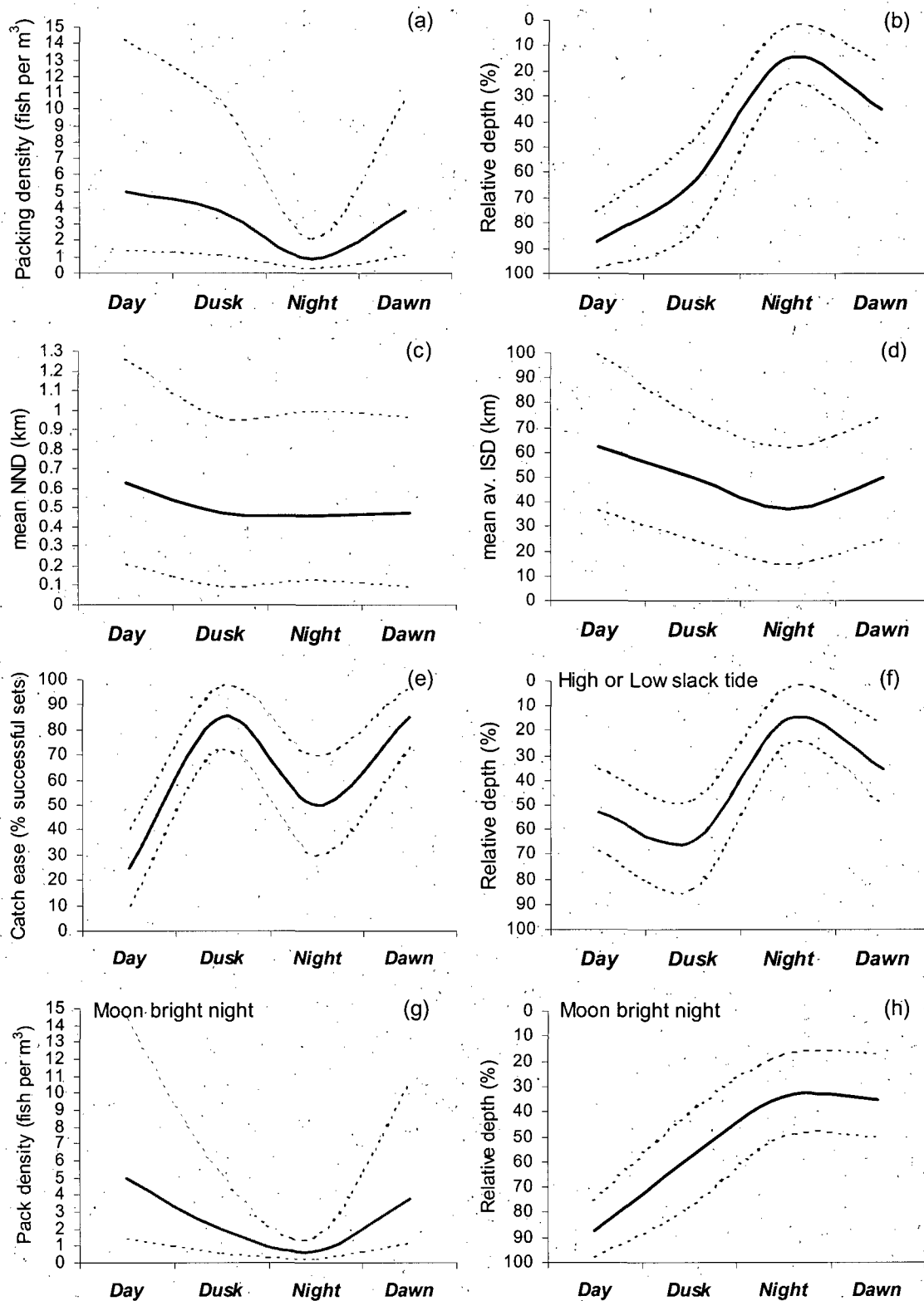


Fig. 5.22 Predicted 'typical' diurnal changes in herring shoal structure and distribution (a-e) and modifications during slack tides (f) and moon bright nights (g & h).

Table 5.4 Qualitative descriptors of predictions for diurnal changes (Note: it is relative, not absolute values of confidence that are important).

Descriptor	Day	Dusk	Night	Dawn
Shoal extent/area	small (Conf=.057) AND medium (Conf=.328) and large (Conf=0.051)	small (Conf=.057) AND medium (Conf=.328) AND large (Conf=.238)	Medium (Conf=.048) AND large (Conf=.435)	small (Conf=.057) AND medium (Conf=.328) AND large (Conf=.238)
Internal dynamics	schooling (Conf=.909)	schooling (Conf=.909) AND shoaling (Conf=.9)	Shoaling (Conf=.9)	schooling (Conf=.909) AND shoaling (Conf=.9)
Size segregation	no result for this descriptor (Conf=1)	often occurs vertically (Conf=.25)	may occur horizontally (Conf=.25) AND often occurs vertically (Conf=.25)	no result for this descriptor (Conf=1)
Shape	horizontally elongated (Conf=.036) AND spheroid (Conf=.043) AND layer (Conf=.043)	horizontally elongated (Conf=.004) AND spheroid (Conf=.043) AND layer (Conf=.043)	Horizontally elongated (Conf=.033) AND layer (Conf=.9)	horizontally elongated (Conf=.004) AND spheroid (Conf=.043) AND layer (Conf=.043)
Cohesion	low (Conf=.028) AND medium (Conf=.119) AND high (Conf=.063)	low (Conf=.028) AND medium (Conf=.119) AND high (Conf=.061)	low (Conf=.165) AND medium (Conf=.002) AND high (Conf=.003)	low (Conf=.028) AND medium (Conf=.119) AND high (Conf=.061)
Feature associations	soft bottom with irregularities in seabed floor (Conf=.9) AND passes with high flushing rate and inlets & bays (Conf=.9)	passes with high flushing rate and inlets & bays (Conf=.9)	Passes with high flushing rate and inlets & bays (Conf=.9)	passes with high flushing rate and inlets & bays (Conf=.9)
Shoal movements	very restricted (fish holding) (Conf=.9)	very restricted (fish holding) (Conf=.9) AND moderate (Conf=.13)	very restricted (fish holding) (Conf=.9)	very restricted (fish holding) (Conf=.9) AND moderate (Conf=.13)
Attack rate of aquatic predators	low (Conf=.14) AND moderate (Conf=.061)	high (Conf=.48)	low (Conf=1)	high (Conf=.48)

(ii) Ocean feeding Norwegian spring spawning herring during daytime over a range of food and predator abundance's.

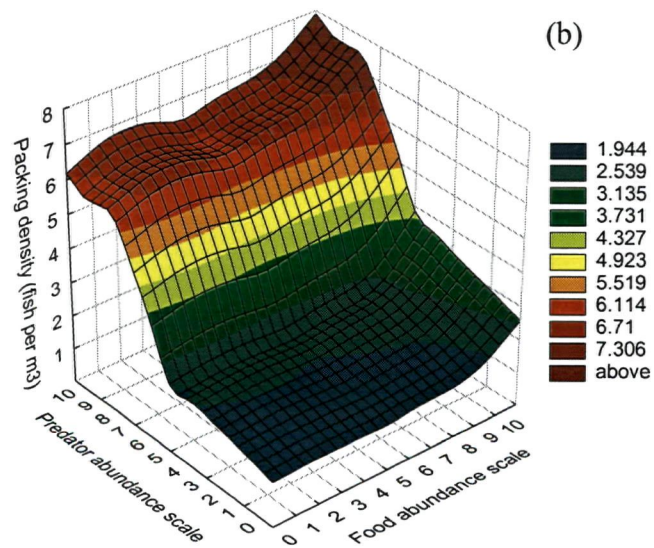
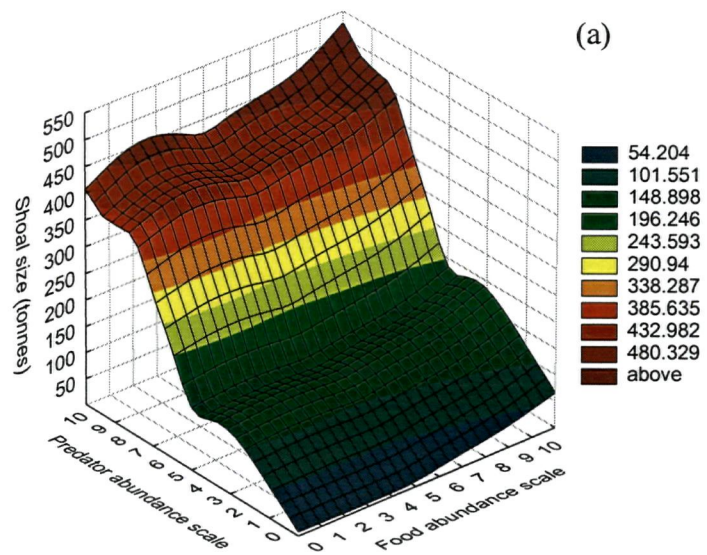
Figures 5.23a-e display plot changes in the average values of quantitative descriptors. Table 5.5 details pertinent changes in qualitative descriptors for 5 combinations of food and predator abundance.

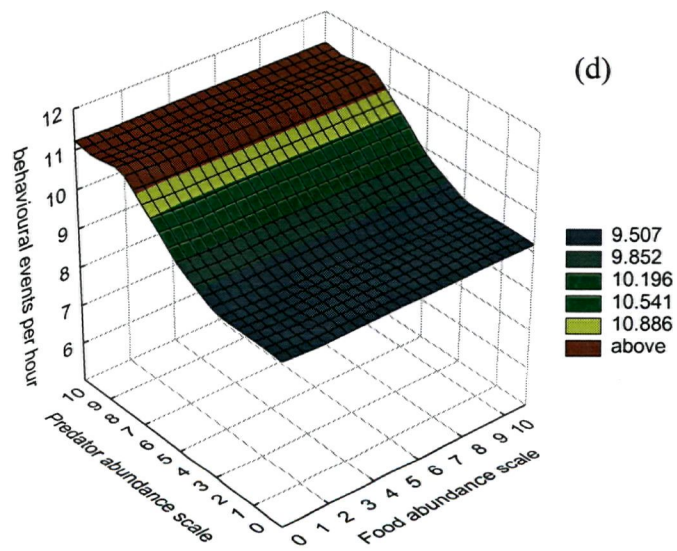
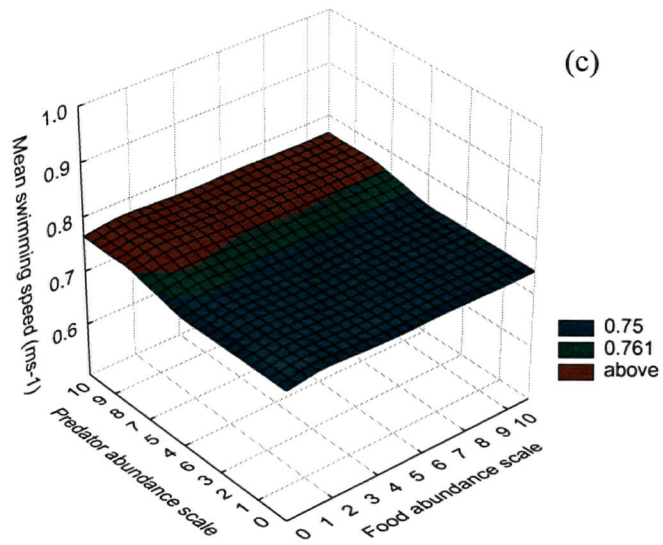
Based on an assumed 'large' to 'very large' stock with mature age structure (12 year classes), two general predictions of CLUPEX for ocean feeding Norwegian spring spawning herring are that the potential range for the stock is fulfilled AND at maximum capacity (Conf. = 0.23), and catchability (q) is low AND medium-low (Conf. = 0.104).

The smallest mean shoal size (25t) is predicted to occur when food and predators are rare (Fig. 5.23a). Increasing food has little effect until food becomes more abundant than 4 units. Beyond this, increasing food supports larger shoals to a maximum of 93t (range 31-171t). Introduction of predators results in a sharp increase in shoal size. As a consequence of the combination between confidence associated with fuzzy sets and the influence of the pseudo-weighting method, a plateau occurs between predators abundance 3-4. Beyond this, shoal size continues to rise as predator abundance increases. The same is true for changes in packing density (Fig. 5.23b) although, without detailed analysis, it is not simple to decipher the causes since multiple factors including food and predator abundance, shoals size, and swimming speed contribute to determining packing density. Changes in extent/area of shoals (Table 5.5) reflect patterns of changes in packing density. Irrespective of food abundance, when predators are abundant, spheroid and layer shaped are predicted with greater confidence and shoals are more cohesive (Table 5.5). Generally, it is evident that predator abundance has a greater influence than food abundance on the determination of shoal structure.

Predictions of shoal dynamics indicate that both mean swimming speed (Fig. 5.23c) and dynamic tendency (Fig. 5.23d) are largely insensitive to changes in food abundance. Increased predator abundance raises swimming activity and the number of behavioural events. Predicted average swimming speeds of around 0.75 ms^{-1} would be considered typical for herring during this life stage. In contrast to shoal dynamics, meso-scale distribution pattern is predominantly determined by food abundance. Shoals are predicted to form tighter clusters as high food abundance sustains good localised feeding opportunities, with heightened predation pressure slightly increasing the intensity of clustering.

The surface of the 3D graphs allude to the tradeoffs that herring perform when balancing predation risk and feeding opportunities. The higher priority of avoiding being eaten results in shoals joining to form larger shoals even when food is low and smaller shoals may be more appropriate for foraging. The 'life-dinner' principle (Dawkins and Krebs, 1979) is mimicked by such trade-offs. The likelihood of shifting location further exemplifies risk-balancing under conflicting pressure (Table 5.5). When predation risk is low and feeding opportunities exist, shoals are predicted to remain in the same feeding location. However, the response during high predation risk depends upon the assumed hunger state of the herring. At low food abundance (hungry fish) a location shift **may** occur; at high food abundance (satiated fish) a location shift is **likely** to occur, herring perhaps being ousted to marginal feeding areas.





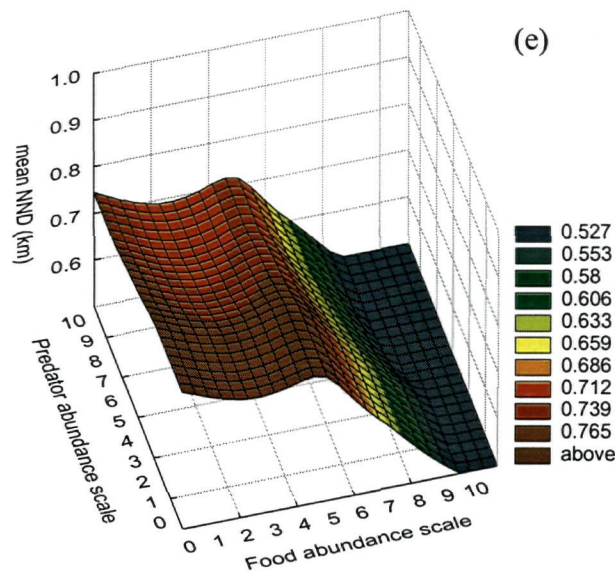


Figure 5.23 Predicted changes in shoal structure, dynamics and distribution of ocean feeding Norwegian spring spawning herring under various regimes of food and predator abundance. (a) shoal size, (b) packing density, (c) average swimming speed, (d) dynamic tendency, (e) mean NND.

(iii) Seasonal changes in Pacific herring

Figure 5.24 displays quantitative predictions of changes in shoals descriptors during 11 different phases of the annual life cycle. Note that the interval between predictions is not related directly to time related. Each prediction is a snapshot in ecological time, since the appropriate temporal scale required to capture the necessary features varies between seasons.

The patterns observed in the model predictions show good general correspondence with observations on herring shoals. Overwintering is recognised as a relatively passive phase in the life cycle during which there is little feeding activity. Very large shoals, or aggregations of shoals, are commonly found distributed as layers deep in the water column, with packing density in the range 0.1-1 fish per m^3 (Mohr, 1971). Overwintering appears to be an exercise in predator avoidance and energy conservation. Reduced swimming activity conserves energy (Huse and Ona, 1996). Large shoal size may not only deter predators but also confer additional energy saving advantages since it has been shown that fish in smaller groups are more timid and nervous and consequently have higher respiratory rates (Pitcher and Parrish, 1993).

Prior to spawning, large winter aggregations break down and move to shallower areas where again they may hold for a while forming dense schools immediately over spawning areas (Hay, 1985). During maturation stage 2-1, large schools have been observed to break up to smaller, very dense, mobile schools (Chapter 2, section 2.2) During spawning, re-aggregation occurs large shoals forming on spawning sites. Immediately after spawning, fish are known to rapidly

disperse in small, low density shoals that swim fast and high in the water column (Hourston and Haegele, 1980; Nøttestad et al. 1996) on the beginning of their migration to ocean feeding grounds. During migration, herring form polarised schools (Misund, 1990) that are typically elongated in the horizontal axis (Mohr, 1971) (Table 5.6).

Ocean feeding shoals of North Sea herring were two times smaller than shoals of Norwegian spring spawning herring recorded during overwintering. Comparison of catches in winter and summer fisheries also suggest that summer aggregations are more mobile (Buerkle and Stephenson, 1990).

Table 5.5 Qualitative descriptors of predictions for ocean feeding Norwegian spring spawning herring.

Predators abundance	Min	Max	Min	Max	Middle
Food abundance	Min	Min	Max	Max	Middle
Shoal extent/area	medium (Conf=.236) AND large (Conf=.455)	small (Conf=.163) AND medium (Conf=.302) AND large (Conf=.224)	small (Conf=.053) AND medium (Conf=.307) AND large (Conf=.369)	small (Conf=.206) AND medium (Conf=.366) AND large (Conf=.094)	Medium (Conf=.382) AND large (Conf=.202)
Internal dynamics	Schooling (Conf=.904) AND shoaling (Conf=.9)	Schooling (Conf=.913) AND shoaling (Conf=.9)	schooling (Conf=.904) AND shoaling (Conf=.9)	schooling (Conf=.913) AND shoaling (Conf=.9)	Schooling (Conf=.913) AND shoaling (Conf=.9)
Shape	Horizontally elongated (Conf=.033) AND spheroid (Conf=.045)	horizontally elongated (Conf=.041) AND spheroid (Conf=.165) AND layer (Conf=.147)	horizontally elongated (Conf=.149) AND spheroid (Conf=.045) AND layer (Conf=.004) AND amorphous (Conf=.12)	horizontally elongated (Conf=.156) AND spheroid (Conf=.165) AND layer (Conf=.15) AND amorphous (Conf=.12)	Horizontally elongated (Conf=.07) AND spheroid (Conf=.045) AND amorphous (Conf=.038)
Cohesion	Low (Conf=.206)	low (Conf=.034) AND medium (Conf=.003) AND high(Conf=.133)	low (Conf=.18) AND medium (Conf=.015) AND high (Conf=.017)	low (Conf=.001) AND medium (Conf=.018) AND high (Conf=.147)	low (Conf=.029) AND medium (Conf=.184)
Location shift likelihood	Unlikely to occur (Conf=.328)	may occur (Conf=.166)	unlikely to occur (Conf=.328)	likely to occur (Conf=.128)	Unlikely to occur (Conf=.328)
Attack rate of aquatic predators	High (Conf=.199) AND moderate (Conf=.2)	high (Conf=.058) AND low (Conf=.124) AND moderate (Conf=.174)	high (Conf=.171) AND low (Conf=.03) AND moderate (Conf=.197)	high (Conf=.014) AND low (Conf=.146) AND moderate (Conf=.156)	High (Conf=.129) AND low (Conf=.1) AND moderate (Conf=.217)

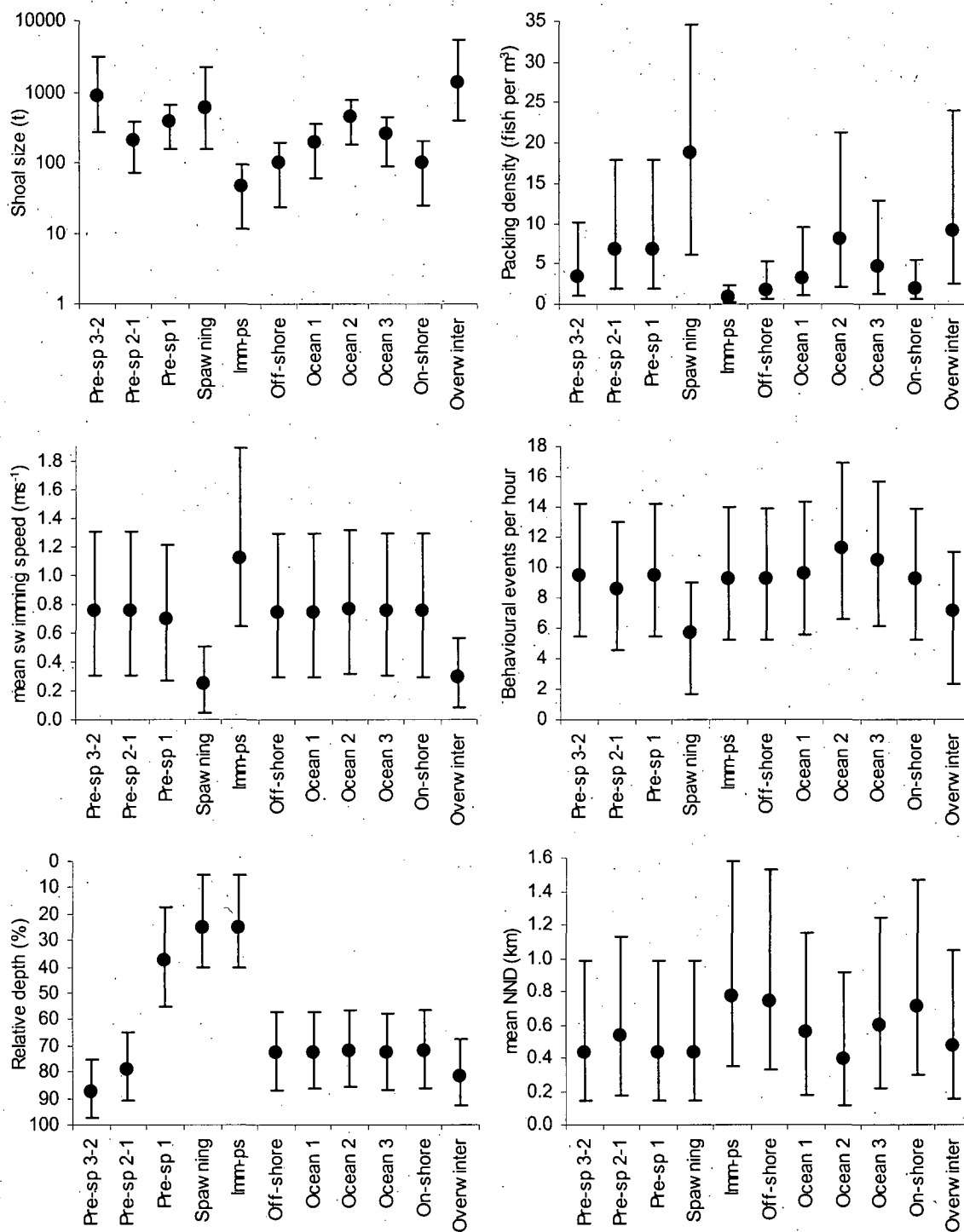


Figure 5.24 Quantitative predictions of seasonal changes in herring shoal structure, dynamics and distribution. Pre-sp: pre-spawning period divided in to 3 maturation stages (based on British Columbia roe herring industry categories), 3-2, 2-1, 1; Imm-ps: Immediate post spawned; Off-shore: offshore migrating; Ocean 1,2,3: ocean feeding phase during 3 stages of summer with changes in food and/or predator abundance and distribution of food; On-shore: onshore migrating; Overwinter: overwintering. Mean NND: mean Nearest Neighbour distance

Table 5.6 Qualitative prediction of seasonal changes in Pacific herring.

	Pre-sp 3-2	Pre-sp 2-1	Pre-sp 1	Spawning	Imm-ps	Off-shore	Ocean 1	Ocean 2	Ocean 3	On-shore	Overwinter
Shoal extent/area	small (Conf=.036) AND medium (Conf=.471) AND large (Conf=.174)	small (Conf=.183) AND medium (Conf=.382) AND large (Conf=.178)	small (Conf=.183) AND medium (Conf=.382) AND large (Conf=.179)	small (Conf=.183) AND medium (Conf=.352) AND large (Conf=.174)	medium (Conf=.153) AND large (Conf=.827)	medium (Conf=.332) AND large (Conf=.378)	small (Conf=.036) AND medium (Conf=.428) AND large (Conf=.221)	small (Conf=.241) AND medium (Conf=.442) AND large (Conf=.103)	Small (Conf=.091) AND medium (Conf=.414) AND large (Conf=.186)	medium (Conf=.341) AND large (Conf=.368)	small (Conf=.193) AND medium (Conf=.278) AND large (Conf=.049)
Internal dynamics	schooling (Conf=.907)	schooling (Conf=.907)	schooling (Conf=.907)	schooling (Conf=.902)	schooling (Conf=.91) AND shoaling (Conf=.9)	schooling (Conf=.905) AND shoaling (Conf=.9)	schooling (Conf=.909) AND shoaling (Conf=.9)	schooling (Conf=.913) AND shoaling (Conf=.901)	Schooling (Conf=.913) AND shoaling (Conf=.901)	schooling (Conf=.905) AND shoaling (Conf=.9)	schooling (Conf=.909)
Size segregation	there is no result for this descriptor (Conf=1)	may occur horizontally (Conf=.014)	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)	horizontally (Conf=.014)	horizontally (Conf=.002)	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)	may occur horizontally (Conf=.002)	there is no result for this descriptor (Conf=1)
Shape	horizontally elongated (Conf=.046) AND layer (Conf=.18) AND bottom amorphous (Conf=.18)	horizontally elongated (Conf=.033) AND spheroid (Conf=.18) AND vertically elongated (Conf=.18) AND bottom amorphous (Conf=.18)	spheroid (Conf=.22) AND vertically elongated (Conf=.22)	amorphous (Conf=.18) AND spawning layer (Conf=.18)	horizontally elongated (Conf=.055) AND amorphous (Conf=.02) AND whispy (Conf=.18)	horizontally elongated (Conf=.046) AND AND spheroid (Conf=.045) AND amorphous (Conf=.007)	horizontally elongated (Conf=.132) AND spheroid (Conf=.045) AND layer (Conf=.005) AND amorphous (Conf=.102)	horizontally elongated (Conf=.164) AND spheroid (Conf=.169) AND layer (Conf=.158) AND amorphous (Conf=.12)	horizontally elongated (Conf=.112) AND spheroid (Conf=.086) AND layer (Conf=.056) AND amorphous (Conf=.07)	horizontally elongated (Conf=.062) AND spheroid (Conf=.047) AND amorphous (Conf=.024)	horizontally elongated (Conf=.041) AND spheroid (Conf=.126) AND layer (Conf=.126)
Cohesion	low (Conf=.154) AND medium (Conf=.048) AND high (Conf=.013)	low (Conf=.279) AND medium (Conf=.053) AND high (Conf=.004)	low (Conf=.154) AND medium (Conf=.052) AND high (Conf=.009)	low (Conf=.155) AND medium (Conf=.049) AND high (Conf=.004)	low (Conf=.195) AND medium (Conf=.025)	low (Conf=.169) AND medium (Conf=.006)	low (Conf=.087) AND medium (Conf=.125) AND high (Conf=.001)	low (Conf=.002) AND medium (Conf=.022) AND high (Conf=.19)	low (Conf=.02) AND medium (Conf=.136) AND high (Conf=.06)	low (Conf=.166) AND medium (Conf=.011)	low (Conf=.024) AND medium (Conf=.003) AND high (Conf=.14)
Fish direction	facing current (Conf=.126)	facing current (Conf=1) AND not sure (Conf=1)	facing current (Conf=1) AND not sure (Conf=1)	facing current (Conf=.128)	not sure (Conf=1)	running with current behind (Conf=.01)	facing current (Conf=1)	facing current (Conf=1)	facing current (Conf=1)	running with current behind (Conf=1) AND not sure (Conf=1)	facing current (Conf=.126)

Association with features	bluffs of steep sided channels (Conf=.9) AND soft bottom with irregularities in seabed floor (Conf=1) AND passes with high flushing rate and inlets & bays (Conf=.9)	bluffs of steep sided channels (Conf=1) AND soft bottom with irregularities in seabed floor (Conf=1)	bluffs of steep sided channels (Conf=1) AND soft bottom with irregularities in seabed floor (Conf=1)	spawning substrate (Conf=1)	non (Conf=1)	non (Conf=1)	frontal zone (Conf=1)	frontal zone (Conf=1)	frontal zone (Conf=1)	non (Conf=1)	bluffs of steep sided channels (Conf=1) AND soft bottom with irregularities in seabed floor (Conf=1) AND passes with high flushing rate and inlets & bays (Conf=.9)
Shoal movements	very restricted (fish holding) (Conf=.9) AND moderate (Conf=.9)	moderate (Conf=.9) AND high (Conf=.17)	low (Conf=.17) AND moderate (Conf=.9)	very restricted (fish holding) (Conf=.917)	moderate (Conf=.9) AND high (Conf=.17)	moderate (Conf=.9) AND high (Conf=.03)	moderate (Conf=.9)	moderate (Conf=.9)	moderate (Conf=.9)	moderate (Conf=.9) AND high (Conf=.03)	very restricted (fish holding) (Conf=.9)
Likelihood of shifting location	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)	unlikely to occur (Conf=.34)	unlikely to occur (Conf=.34)	unlikely to occur (Conf=.34)	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)
Attack rate of aquatic predators	low (Conf=.242) AND moderate (Conf=.088)	low (Conf=.204) AND moderate (Conf=.209)	low (Conf=.246) AND moderate (Conf=.088)	low (Conf=.16) AND moderate (Conf=.101)	high (Conf=.397) AND low (Conf=.085) AND moderate (Conf=.452)	high (Conf=.15) AND low (Conf=.068) AND moderate (Conf=.208)	high (Conf=.113) AND low (Conf=.133) AND moderate (Conf=.232)	high (Conf=.031) AND low (Conf=.204) AND moderate (Conf=.226)	high (Conf=.11) AND low (Conf=.15) AND moderate (Conf=.243)	high (Conf=.147) AND low (Conf=.072) AND moderate (Conf=.208)	low (Conf=.191)

Comparison with new data - model validation

Model predictions of temporal changes in shoal structure and distribution during pre-spawning maturation are compared to real data collected in Spiller channel, British Columbia 1998 (52°20' N, 128°12' W). For the comparison, the situation observed in the field is mimicked as close as possible for the model input parameters. Real data focuses on the period 7th - 15th March 1998 during which time a change in maturation occurred from stage 3 (gonads prominent but immature) to stage 1 (gonads bulging and ripe) (Industry defined roe herring categories; Armstrong, 1986). Eighty-four shoals were recorded during daylight periods, and on the 7th - 8th March a storm occurred. The following inputs were assumed to be fixed for all predictions: time of day - daytime, 8 age classes; relative stock size small and medium; local abundance - 26500 t; all predator species present; predator abundance scale = 3; water depth = 80m; birds distributed in concentrated patches; tide state - ebb.

Detailed comparison with observations is provided in Fig. 5.25 and Table 5.7. Predicted shoal size was considerably larger during early maturation stages than that observed, but during stages 2 and 1 there was closer correspondence. The general prediction that shoal size would decline from stage 3 to 2 and increase again during stage 1 did not occur, although observed values were within the range predicted (Fig. 5.25a). Predictions for packing density were in accordance with observed patterns of a density index scale; density being higher during later stages of maturation (Fig. 5.25b and Table 5.7). Determination of the top 3 observed shoal shapes for each period confirmed predictions that spherical shoals are more prevalent during later stages of maturation. Furthermore, the predicted association of shoals with rock outcroppings and sides of steep sided channels was upheld; forty two percent of all shoals were associated with a physical feature, and of these, 92% were associated with rise/drop-off from rocky outcroppings of the bottom topography.

Predictions of distribution patterns reflect a general trend of decline in distance between neighbour shoals and average distance among all shoals, reflecting a tendency for shoals to aggregate in tighter clusters in a reduced geographic range as maturation progresses. Whilst the pattern is supported by the data to a partial extent, the accuracy of the predicted values varies. The range of mean NND values overlaps with the observed data, whereas those of mean average ISD do not (Fig. 5.25c & d). A point worth noting is the prediction that on the 8th March, during the storm, distribution of shoals was markedly less clustered, as was observed to be the case. Although the relative depth distribution shows apparently little correspondence with specific daily observations (Fig. 5.25e), a general tendency for shoals to be found higher in the water as maturation progresses is predicted and supported by the significant correlation in Table 5.8.

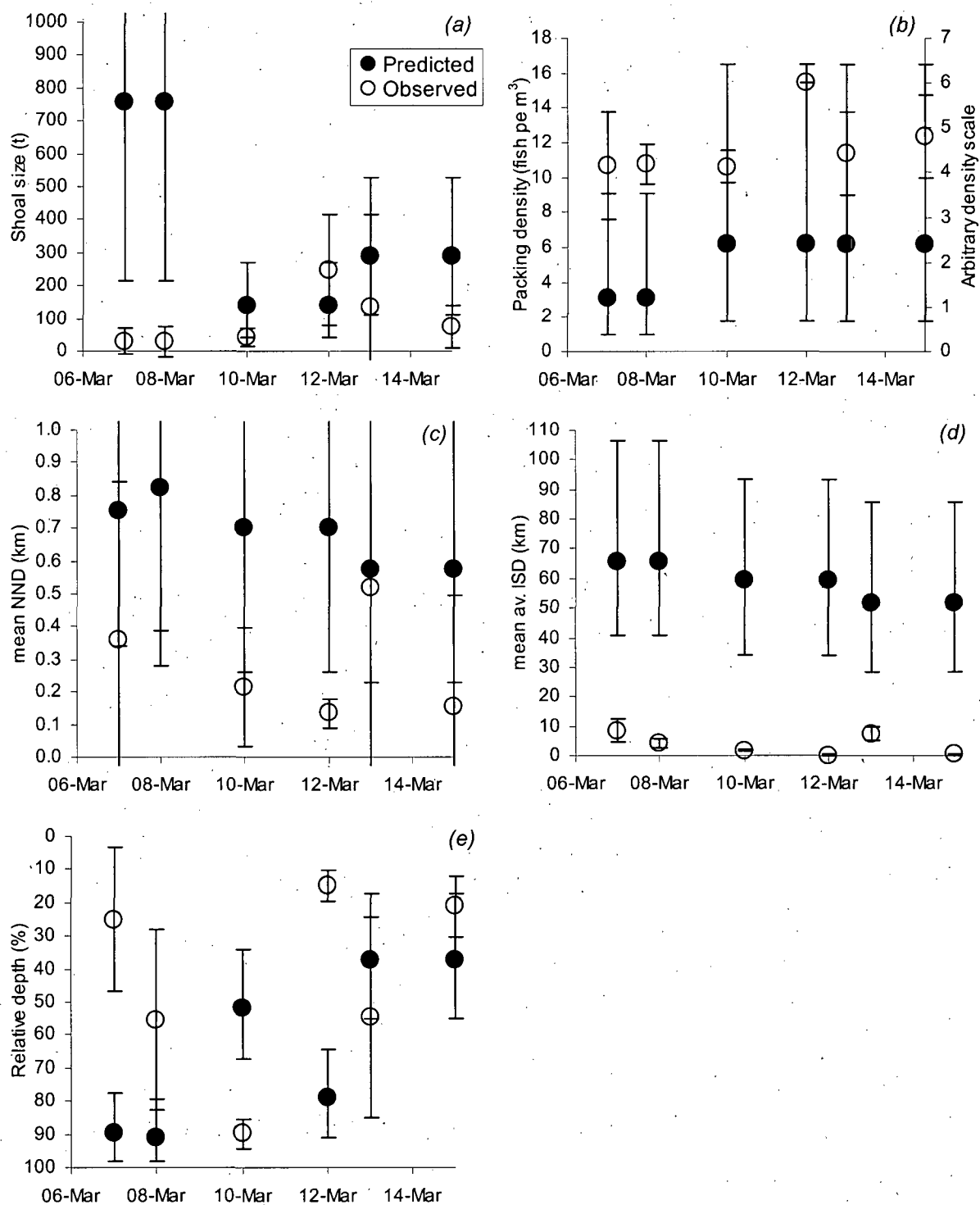


Figure 5.25 Predicted and observed structure and distribution of herring shoals. Predicted data with range bars and observed data with standard deviations. Observed numbers of shoals: 7th March (36), 8th March (5), 10th March (15), 12th March (4), 13th March (14), 15th March (10).

Table 5.7 Predicted qualitative temporal changes in pre-spawning Pacific herring shoals.

	07-Mar	08-Mar	10-Mar	12-Mar	13-Mar	15-Mar
Shoal area/extent	small (Conf=.036) AND medium (Conf=.446) AND large (Conf=.246)	small (Conf=.036) AND medium (Conf=.446) AND large (Conf=.246)	small (Conf=.183) AND medium (Conf=.352) AND large (Conf=.249)	small (Conf=.183) AND medium (Conf=.352) AND large (Conf=.249)	small (Conf=.183) AND medium (Conf=.353) AND large (Conf=.25)	small (Conf=.183) AND medium (Conf=.353) AND large (Conf=.25)
Internal dynamics	schooling (Conf=.905)	schooling (Conf=.905)	schooling (Conf=.905)	schooling (Conf=.905)	schooling (Conf=.904)	schooling (Conf=.904)
Size segregation	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)	may occur horizontally (Conf=.014) AND there is no result for this descriptor (Conf=1)	may occur horizontally (Conf=.014) AND there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)	there is no result for this descriptor (Conf=1)
Shape	horizontally elongated (Conf=.066) AND layer (Conf=.18) AND bottom amorphous (Conf=.18)	horizontally elongated (Conf=.086) AND layer (Conf=.18) AND bottom amorphous (Conf=.18)	horizontally elongated (Conf=.033) AND spheroid (Conf=.18) AND vertically elongated (Conf=.18) AND bottom amorphous (Conf=.18)	horizontally elongated (Conf=.033) AND spheroid (Conf=.18) AND vertically elongated (Conf=.18) AND bottom amorphous (Conf=.18)	spheroid (Conf=.22) AND vertically elongated (Conf=.22)	spheroid (Conf=.22) AND vertically elongated (Conf=.22)
Cohesion	low (Conf=.164) AND medium (Conf=.008) AND high (Conf=.011)	low (Conf=.164) AND medium (Conf=.008) AND high (Conf=.011)	low (Conf=.287) AND medium (Conf=.012) AND high (Conf=.001)	low (Conf=.287) AND medium (Conf=.012) AND high (Conf=.001)	low (Conf=.164) AND medium (Conf=.012) AND high (Conf=.007)	low (Conf=.164) AND medium (Conf=.012) AND high (Conf=.007)
Fish direction	facing current (Conf=.126)	facing current (Conf=.126)	facing current (Conf=1)	facing current (Conf=1)	facing current (Conf=1)	facing current (Conf=1)
Association with physical features	hard bottom with rock outcroppings (Conf=.9) AND bluffs of steep sided channels (Conf=1) AND passes with high flushing rate and inlets & bays (Conf=1)	hard bottom with rock outcroppings (Conf=.9) AND bluffs of steep sided channels (Conf=1) AND passes with high flushing rate and inlets & bays (Conf=1)	bluffs of steep sided channels (Conf=1) AND passes with high flushing rate and inlets & bays (Conf=1)	bluffs of steep sided channels (Conf=1) AND passes with high flushing rate and inlets & bays (Conf=1)	hard bottom with rock outcroppings (Conf=.17) AND bluffs of steep sided channels (Conf=1) AND passes with high flushing rate and inlets & bays (Conf=1)	hard bottom with rock outcroppings (Conf=.17) AND bluffs of steep sided channels (Conf=1) AND passes with high flushing rate and inlets & bays (Conf=1)
Shoal movements	very restricted (fish holding) (Conf=.9) AND moderate (Conf=.9)	very restricted (fish holding) (Conf=.9) AND moderate (Conf=.9)	moderate (Conf=.9) AND high (Conf=.17)	moderate (Conf=.9) AND high (Conf=.17)	low (Conf=.17) AND moderate (Conf=.9)	low (Conf=.17) AND moderate (Conf=.9)
Aquatic predator attack rate	low (Conf=.229) AND moderate (Conf=.14)	low (Conf=.229) AND moderate (Conf=.14)	low (Conf=.189) AND moderate (Conf=.243)	low (Conf=.189) AND moderate (Conf=.243)	low (Conf=.234) AND moderate (Conf=.14)	low (Conf=.234) AND moderate (Conf=.14)

Table 5.8 Observed temporal changes of shoal structure and distribution. Spiller channel, central coast, B.C. March 1998. Correlation coefficients marked in bold are significant at the 5% level.

	Water depth	Rel. depth (%)	Rel. height (%)	Ln Biomass	Density scale
Time	-0.19	-0.16	0.10	0.28	0.297

Robustness and sensitivity analysis

The total number of possible input combinations to the model is approximately 1.03×10^{33} , so for practical purposes, random testing was used to assess the robustness and internal consistency of the model. Available computing power limited the maximum number of tests to 90,000. No internal logical consistency errors were detected, indicating the model is robust since it is capable of deriving required output for any particular input. However, the validity of the input is the onus of the user. Figure 5.26 summarises data on utilisation of model parameters during 90,000 random runs. Almost all *variables* (input and output quantitative attributes and descriptors) are fully utilised during each run. Similarly, the majority of *qualifiers* (attributes and qualitative descriptors) are also required for any given run (70% of qualifiers are used in 100% of 90,000 tests). The more even spread in the distribution of rule utilisation is indicative of the large number of alternative runs that are possible.

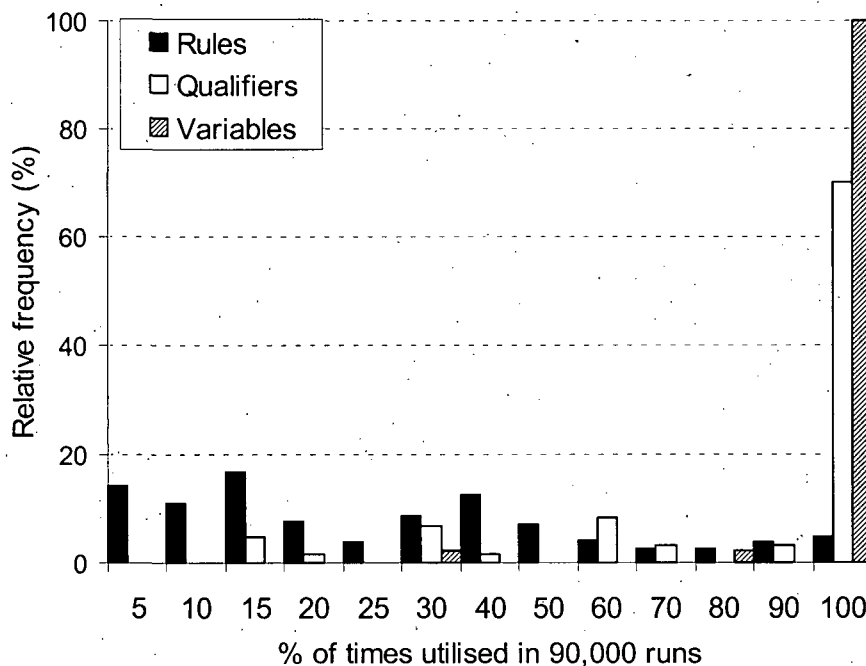


Figure 5.26 Utilisation of rules, qualifiers (attributes and qualitative descriptors) and variables (quantitative descriptors and formulas) during 90,000 random test runs of the complete system.

Five elements contribute to the sensitivity of the model. Values of the 35 potential inputs, pseudo-weight variables used to mimic seasonal changes in motivation, fuzzy set definitions

(shape and limits of sets), confidence values associated with rules, and weights used during defuzzification of quantitative output descriptors. The model can be characterised as an 'over-parameterised' system. Consequently, detailed sensitivity analysis of each variable is not a viable option. The most appropriate method of sensitivity testing was considered to be to systematically remove rules, thereby degrading the system in steps and assessing the impact by examining the consequence on the output results as information is lost.

Two approaches were used to define groups of rules for systematic removal: (1) *Rule loss*: rules were classified into 12 discrete groups according to their percentage utilisation in 90,000 random runs of the complete system (Table 5.9). At each removal step, a complete group of rules was removed; (2) *Attributes loss*: attributes were classified by type (external abiotic, external-biotic, internal biological, internal motivation) and placed into 5 groups (A-E) based on their percentage utilisation in 90,000 random runs of the complete system (Table 5.10). At each removal step, the rules associated with the attributes from each utilisation group were removed. This procedure was carried out for groups A-D. Group E, whose attributes are used in all runs can be considered critical to system operation since they are used in 100% of runs. Their removal would of course, result in failure of the system.

The number of rules remaining after each stage of information loss is detailed in Table 5.11. For both approaches, 10,000 random runs of the degraded system were made after each step of rule removal. It was considered that 10,000 runs was sufficient since comparison of the parameter utilisation between 90,000 and 10,000 runs of the complete system revealed sums of residuals, -0.5 for qualifiers and zero for variables. This considerably reduced the time for each random run of the removal steps.

Modification in predictive capability was assessed by comparing the range of values predicted for structure, dynamics and distribution by the degraded system to that obtained from 90,000 runs of the complete system for a specific scenario (Fig. 5.27). In addition, both approaches were evaluated on information loss. The criteria used for *Rule loss* approach was percentage of qualifiers never used, percentage variables never used and number of failed runs; for *Attribute loss*, percentage of rules never used, percentage variables never used and number of failed runs (Fig. 5.28).

Table 5.9 Rules classified in 12 groups according to their utilisation in 90,000 random runs of the complete system.

Rule # in each % utilisation group												
0-5	6-10	11-15	16-20	21-25	26-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
46	180	55	20	35	122	61	88	139	10	132	133	163
80	49	183	24	138	124	123	177	33	6	165	96	161
81	62	17	135	44	36	16	142	14	38	11	169	157
39	162	31	45	60	64	146	102	21	13	127	12	159
40	178	143	108	128	63	34	107	32	57	136	145	131
82	170	48	110		164	72	104	15			125	9
47	87	172	2		29	140	119	18			130	126
78	109	25	86		182	23	106	100			70	167
184	58	151	115		95	134	65					
50	75	112	54		37	175	120					
51	152	26	90		137	69	97					
77	67	7	116		94	73						
144	160	5	148		101	141						
174	181	68	89			153						
3	53	129	121			59						
74	66	4	114			84						
76	113	98	118			43						
1	83	111	79			71						
154	56	41	117			8						
158	176	91				147						
171		93				19						
155		99				22						
166		105				42						
179		28				149						
27		30				85						
156		92										
		103										
		52										
		173										
		150										
		168										

Table 5.10 Table of attribute utilisation groups in 90,000 random runs of the complete system. Attribute types: EA-External abiotic, EB- External biotic, IB-Internal biological, IM-Internal motivational.

Utilisation Group #	Attribute name	Qualifier #	Attribute type	% utilisation in 90,000 random runs
A: 1-20%	Water temperature regimes	24	EA	14.3
	Area of available of spawning habitat	23	EA	14.3
	Food patches associated with specific ocean features	7	EB	14.3
	Size of food	9	EB	17.6
B: 21-40%	State of moon cycle	27	EA	25
	Typical topography and substrate features are:	22	EA	25.5
	Relative depth of predominant current (% of bottom)	18	EA	28.6
	Direction of current	19	EA	28.6
	Distribution of birds	15	EB	36.6
C: 41-60%	Feeding mode	4	EB	57
	Food depth distribution	6	EB	57
	Distance between food patches	8	EB	57
	Competition from other species	26	EB	57
	Hunger status	14	IM	57
D: 61-80%	State of tide	21	EA	62
E: 81-100%	Time of day	1	EA	100
	Water depth	17	EA	100
	Strength of current	20	EA	100
	Weather conditions	25	EA	100
	Fish showing general avoidance response	29	EA	100
	Chose description that best describes the weather	57	EA	100
	Feeding status	3	EB	100
	Food abundance	5	EB	100
	Abundance of aquatic predators	12	EB	100
	Pre-spawning maturation stage (British Columbia herring roe categories)	16	IB	100
	Feeding priority	30	IM	100
	Avoid predation risk priority	31	IM	100
	Reproduce priority	32	IM	100
	Energy saving priority	33	IM	100

Table 5.11 Remaining rules at each rule removal stage of for 2 formal relaxation approaches. Note that the complete system comprised of 186 rules.

Number of rules remaining in system			
<i>Rule loss</i>		<i>Attribute loss</i>	
Rule utilisation group		Attribute utilisation group	
0-5%	158	A: 0-20%	172
6-10%	138	B: 21-40%	161
11-15%	107	C: 41-60%	146
16-20%	88	D: 61-80%	145
21-25%	83		
26-30%	70		
31-40%	45		
41-50%	34		
51-60%	26		
61-70%	21		
71-80%	16		
81-90%	8		

Comparison of the two approaches reveals that the number of rules removed has greater impact on the degradation of the system than the type of rules associated with specific attributes. In the scenario examined, when rules that are normally utilised in 10% of all runs are removed, the predictions deviate drastically from that of the complete system (Fig. 5.27). Using Table 5.9 it is possible to identify exactly which rules these are. Removal of rules in the 0-5% category has negligible impact. When rules normally used 25% of the time are removed, all variables fail to be used and the system has failed completely (Fig. 5.28a). In contrast, when rules associated with specific attributes are systematically removed, the system does not degrade so rapidly. Even when rules associated with attributes that are normally used up to 80% of the time, there is little observable impact on the system; predictions do not deviate measurably from the complete system (Fig. 5.27). This result occurs because few rules have been removed; the system remaining with 145 of the original 186 rules (Table 5.11). Table 5.10 identifies those attributes whose removal has little apparent effect on the system. It might seem then that these attributes are in effect redundant, this is not the case for two reasons. First, recall that the predictions relate only to the one specific scenario being examined; if I were to chose a different scenario, these attributes may be critical for making predictions. Second, recall that the range of predicted values is based on a random set of runs; users do not query the system in random, hence attributes utilised only occasionally by random testing may be used considerably more frequently by a users directed query approach.

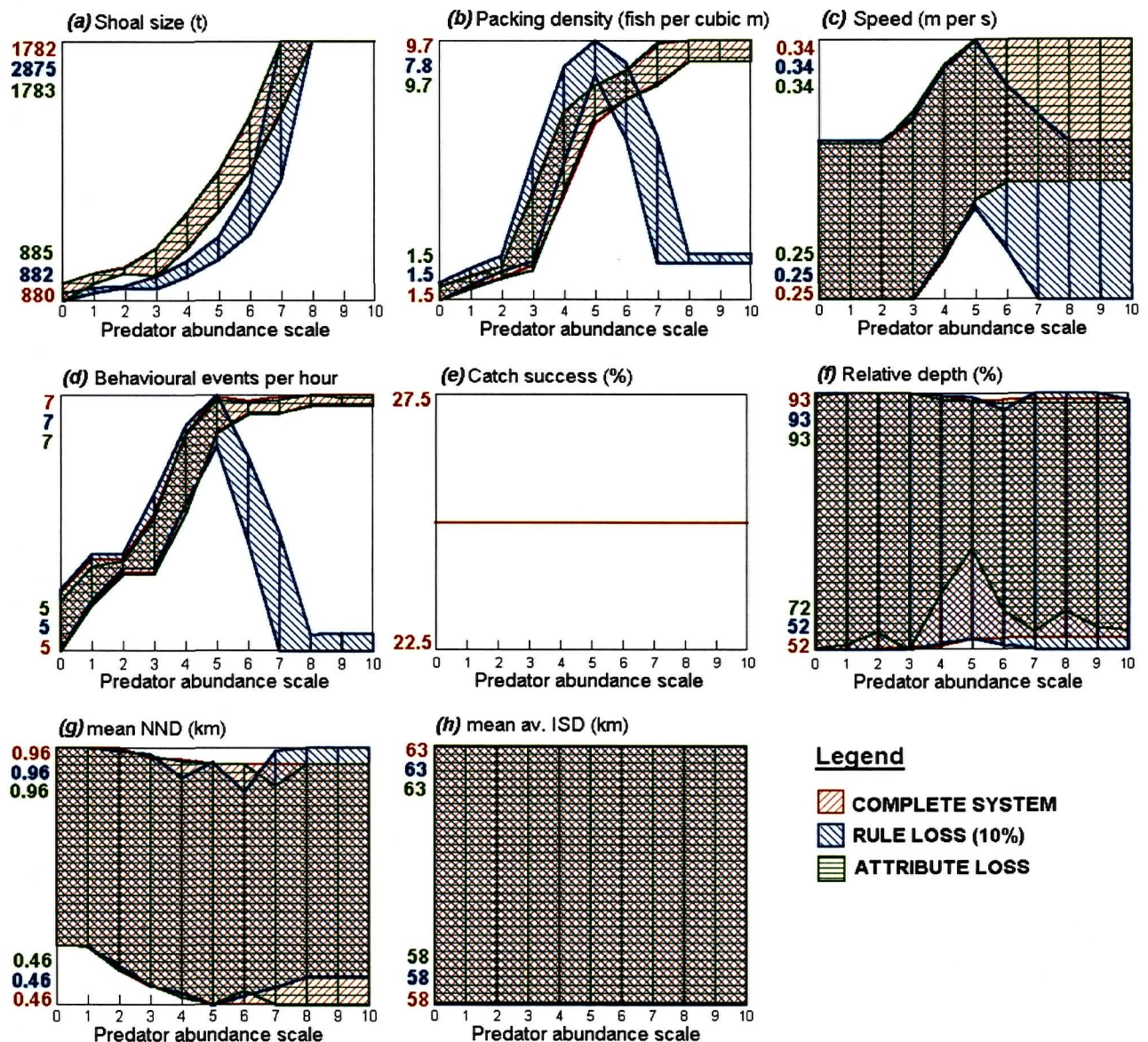


Fig. 5.27 Comparison of predictive capability of model after removal of rules. Predictions from the complete system (90,000 random runs; Red range) are compared with those from the Rule loss (10% - rules utilised up to 10% of the time in 90,000 runs; Blue range) and Attribute loss (Group E - rules removed associated with attributes used up to 80% in 90,000 runs). Each graph superimposes 3 predictions of the range of values predicted for a single quantitative shoal descriptor over a range of values for predator abundance during daytime of the overwintering life phase. Values on Y-axes represent maximum and minimum scales for each descriptor.

The seemingly anomalous result that the number of failed runs decreases as more rules are removed in the *Attribute loss* method is a consequence of the seeded random method used for test runs. The specific starting sequences for the firing of rules resulted in attribute utilisation groups C:60 and D:80 finding less blind endings in the paths followed.

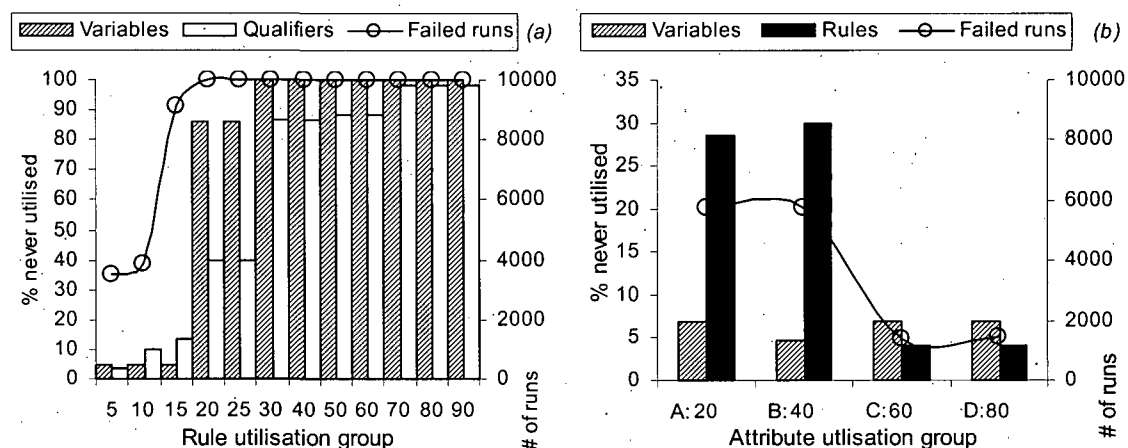


Figure 5.28 Information loss after systematic removal of rules using 2 approaches; (a) Rule loss, (b) Attribute loss. Number of random test runs is 10,000.

As previously mentioned, fuzzy set definitions, weightings used to apply effects of seasonal motivation and confidence factors associated with rules, are recognised as sensitive elements of the model. Yet, more importantly they are the very elements that provide flexibility. These factors together with the weights used for defuzzification, can be easily altered providing the model with high adaptive capability.

5.5 Discussion

I have presented a heuristic model that predicts the structure, dynamics and meso-scale distribution of shoals of adult migratory herring. Its foundations assume that individual behavioural responses to changes in external (biotic and abiotic) and internal (biological and motivational) conditions are manifested as modifications at the shoal level. Given that our understanding of the ecological mechanisms involved is at best patchy, attempting to predict these modifications is an ambitious task. Developed in the framework of an expert system, the model utilises fuzzy logic to capture and integrate scientific and local knowledge, the rationale being to close some existing gaps in our understanding by maximising all potential data sources (Mackinson and Nøttestad, 1998). Details of data collection techniques and comparison of knowledge sources used within the model are provided in Chapter 4. Discussion here will be limited to the strengths, weaknesses and applications of the model and approach in general.

Comprised of more than 35 potential inputs and 23 outputs, the model uses a 'bottom up' approach to link multiple causative and inter-related factors. In a review of fishery science related expert system applications (Saila, 1996) offers a list of only 18 judged to be of relevant. Of these, only 2, Aoki et al. (1989) and Fuchs (1991), both non-fuzzy systems, address linkages between fish and environment. Although different strategies are used, both systems develop rules relating environmental variables to fishing conditions in a manner that serves primarily to reconstruct past observations. The underlying approach used here is conceptually different, the

relations being developed to imitate ecological and behavioural mechanisms that drive adaptations in shoal structure, dynamics and distribution. As a consequence, the model has greater capability to forecast new situations.

Other models derived from branches of artificial intelligence have also been applied in the environmental field. Huse and Giske (1998) demonstrate another 'bottom up' type of approach. They develop an individual based model that uses a genetic algorithm optimisation to evolve fish behaviour due to differences in survival resulting from spatial heterogeneity in habitat. Vabø and Nøttestad (1998) visualise internal school dynamics using a cellular automata individual based model founded on individual decision rules. Neural networks are also increasingly being used in fisheries as alternatives to multi-factor analysis methods such as multi-dimensional scaling and multiple regression. Aoki and Komatsu (1997) used a neural net to predict winter catch of young sardine based on biological, hydrographic and climatic factors.

In comparison with more conventional modelling techniques that rely on describing relationships with mathematical functions, the fuzzy expert system is similarly capable of describing continuous relationships and including feedback effects. In contrast, it does not suffer from the same constraints; when knowledge is incomplete, rules can still be used to describe 'pieces' of relationships without making gross assumptions. Moreover, the transparency of the model, both in terms of its intuitive operation and the ability for users to access expert knowledge when questioning its reasoning, contrasts with the apparent 'mysteriousness' of many analytical models.

The model is highly flexible in its predictive capability being able to forecast shoal structure, dynamics and meso-scale distribution across different temporal scales. Accuracy of prediction is dependent on the *accuracy* of information captured in rules and also on the *realism* of the input provided by the user. Predicted diurnal changes in shoal structure (Fig. 5.22) confer well with the typical 'Type-I' pattern (Nielson and Perry, 1990) observed in herring throughout most of their adult life cycle (e.g. Radakov, 1960; Blaxter and Holliday, 1969; Thorne, 1977; Blaxter, 1985; Buerkle and Stephenson, 1990; McCarter et al. 1994; Mackinson et al. 1999b). Surveys on the Pacific coast 1971-1982 found daytime herring schools at 40m deep dispersing to form relatively uniform, widespread, single target layers between 10-30m during the night (Mathisen et al. 1983). Thorne (1977) noted that at night, school volume was higher and herring were dispersed at lower densities and over wider areas with considerably less patchiness. Mean daytime densities were 9-10.4 fish per m³. Examination of the echo traces also indicated an extreme trend in distribution towards the shore at night. These specific observations are in accordance with those predicted by CLUPEX. Modifications to the typical diurnal pattern occur under several situations and are included in the model; cessation during late stages of maturation immediately prior to spawning (Hay, Pierce, McEachen, and Gordon, interview pers. comms); occurrence of daytime pelagic and surface schools, thought to be related to tide (Ellis, Heglund, Jim, Thomas, Lenic, Pierce and Carr, interview pers. comms; DFO, 1991) and/or feeding opportunities (Melle

et al. 1994); early rising and rapid dispersion during moon bright nights (Boroevich, Carr, Hunt, Reid, Lenic and Wilson, interview pers comms; Butcher, 1975; DFO, 1991).

Predictions of diurnal change in meso-scale distribution pattern (mean NND and mean \overline{ISD}) are generalised from rules based on limited observations during a single life phase (Mackinson et al. 1999). Improving the resolution of the knowledge may lead to rule alterations/additions that increase the specificity of predictions. This point is further emphasised in the comparison of predicted and observed changes during pre-spawning maturation. Whilst some predictions were validated, lack of place specific detailed local knowledge resulted in poor adherence on some aspects. This is by no means a failure, rather it is learning. The adaptive capability of the model ensures that with incorporation of specific local knowledge, predictions could improve substantially.

Several mechanisms are implemented to avoid predictions breaking down due to inaccurate or unrealistic input by the user. Foremost is the sequence in which rules are fired; the user is 'led' through the run in a logical sequence. Second, a custom help facility ensures that the user fully understands the questions. Third, placebo choices offer the user the ability to ignore conditions they are not sure of. Fourth, values outside of expected ranges are flagged. Even with these safeguards, the onus is ultimately on the user to provide realism in the scenario they develop when providing input.

Precision of predicted values is dependent on two facets, the precision of knowledge and the values used as weights in defuzzification. Since we do not start with high precision in our knowledge, it is unreasonable to expect high precision in the output. More important for the present model is the ability to predict general patterns. Values used as weights in defuzzification represent low-medium-high values from published field observations. Such data is scant, and that which is available, is uncertain and imprecise. Consequently, values are applied generally in the model thus diminishing the ability to predict specific instances. Fortunately, the defuzzification weights are one of the adaptive components of the model that permit the ability to tune predictions toward specific circumstances when better knowledge exists.

Behavioural tradeoffs known to occur when herring face conflicting interests are mimicked within the model by a pseudo-weighting method and confidence factors associated with rules. Whilst it is recognised that the pseudo-weighting is not most appropriate method, the model successfully captures the essential behaviour we expect to observe based on published field and experimental observations. The surface of the 3D graphs (Fig. 5.23) describe the quantitative responses to effects of predators (Major, 1978; Hager and Helfman, 1991; Pitcher et al. 1996; Krause et al. 1998; Nøttestad and Axelsen, 1999) and food (Robinson and Pitcher, 1989; Robinson, 1995). Furthermore, they allude to the risk balancing tradeoffs demonstrated to occur when fish are faced with evaluating predation risk and feeding opportunity (Pitcher et al., 1976; Lima and Dill, 1990; Morgan and Colgan, 1987; Morgan, 1988; Godin, 1990; Milinski, 1993).

An important feature of the model is that predictions constitute testable hypotheses on which to base future experiments and field observations.

Seasonal dynamics in the shoal structure and distribution can be generated by providing an annual sequence of input parameters across different life stages (Mackinson, 1999a). Further development of the model hopes to provide a graphic interface to display these dynamics and examine the consequence of habitat constraints on shoal distribution pattern (Chapter 6, section 6.1; Newlands and Mackinson, in prep).

Systematic removal of rules from the complete system revealed that the number of rules removed has greater impact on the predictive ability than on the type of attributes removed. Since users are unlikely to supply random input for predictions, none of the rules or attributes are redundant; even though they may be utilised only occasionally, they are required as a necessity under specific circumstances. Rules whose confidence value is low (due to uncertainty) may similarly seem to contribute little, yet their presence may again be critical to make prediction for specific circumstances.

The number of rules required to make predictions is dependent on the scale/resolution that the system is intended for. The current system is intended to predict the structure, dynamics and distribution of herring shoals on a broad scale. It incorporates a considerable amount of knowledge at this resolution. A smaller system with less rules could be constructed; it would be complete and be even more generalised in its predictions. A larger system, perhaps modularised, could be constructed to make more precise predictions; however, unfortunately there is currently a lack of knowledge required to construct rules for such a system.

The model detailed here is capable of predicting state dependent, meso-scale spatio-temporal changes in the structure, dynamics and distribution of herring shoals. The resolution of its predictions are appropriate for addressing some issues of fisheries management outlined in the introduction. Using a similar approach to develop a rule set to describe fishing fleet dynamics is an attractive future development that would allow evaluation of the effects of changes in fish and fleet distribution and dynamics on catch rates. This aspect is elaborated upon in chapter 6. Other potential uses for this system include; training herring fishery managers on distribution and behaviour of herring; a foundation for development of non-linear behavioural models in other schooling fish (may include additions such as a neural network); a formal framework for combining local and scientific knowledge.

Use of an expert system is an admission that our knowledge is incomplete and uncertain, yet through building and testing it is a move toward practicality, recognising that decisions based on qualitative and sometimes incomplete knowledge is still better than making decisions without any understanding (Saila, 1996). Heuristic models in general offer considerable future opportunities, a point emphasised by Hilborn and Mangel (1996), who comment, "although the output of most models is numerical, the most influential models are the ones in the numerical output is not needed to guide the qualitative understanding".

Chapter 6

Applications and Implications

6.1 Introduction

"The central challenge in the conduct of any commercial marine fishery is the proper division of the relevant biological population into two categories: dead and alive"

Mundy et al. (1985)

The importance of harvest strategies has been discussed by many authors (e.g. Sissenwine and Kirkley, 1982; Hilborn, 1986; Hall et al. 1988; Hilborn and Walters, 1992; Walters and Parma, 1996). Comparisons indicate that although a fixed escapement strategy would provide greatest long term yields, fixed harvest rate strategies (Fig 6.1) are more robust for species such as herring that naturally exhibit great variation in abundance. However, even when harvest strategies are clearly defined, failure to successfully implement the strategy can result in a significant increase in the vulnerability to over-exploitation; if year to year control cannot be achieved, the harvest strategy is ineffective and all the efforts focused to determine the proper level of harvest count for nothing (Mundy et al. 1985). In short, if control tactics are inadequate, long-term harvest strategies cannot be fulfilled (Fig 6.2).

Within the course of a season, harvest control consists of a series of decisions to harvest or not to harvest. Studies of harvest control tactics indicate that regulations based on effort limitation as opposed to annual catch quotas are a more robust means of implementing fixed harvest strategies (e.g. Hilborn, 1986), although little attention has been given to examining the suitability of access (or 'exposure') limitation, on shoaling species such as herring. The principle of exposure limitation is to ensure that only the desired fraction of the stock are exposed to fishing through the implementation of space-time restrictions. Usually, such restrictions on fishing are imposed for management convenience or to protect a component of the resource during a vulnerable period such as spawning (Sissenwine and Kirkley, 1982). To develop restrictions such as those based on the use of space-time tactics, there is need to understand the processes responsible for producing observed spatial distributions and gather distribution and movement data required to set areas/times correctly (Walters and Parma, 1996). The research presented in this thesis is focussed on providing a clearer understanding of how behaviour determines the distribution and structure of herring shoals; information necessary to design robust in-season harvest tactics and reduce reliance on total allowable catches based on pre-season stock forecasts.

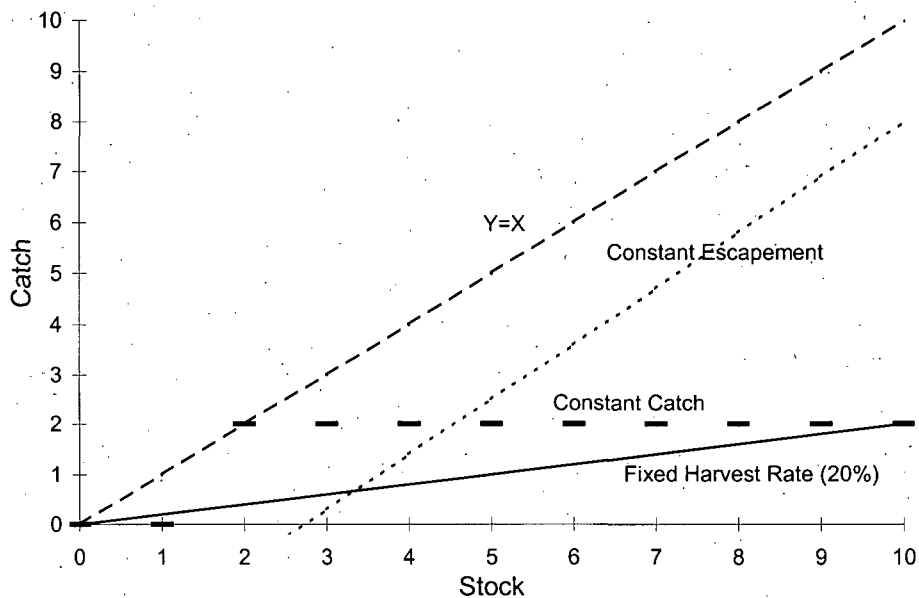


Figure 6.1 Simple stock-size-dependent harvest strategies (re-drawn from Hilborn and Walters, 1992).

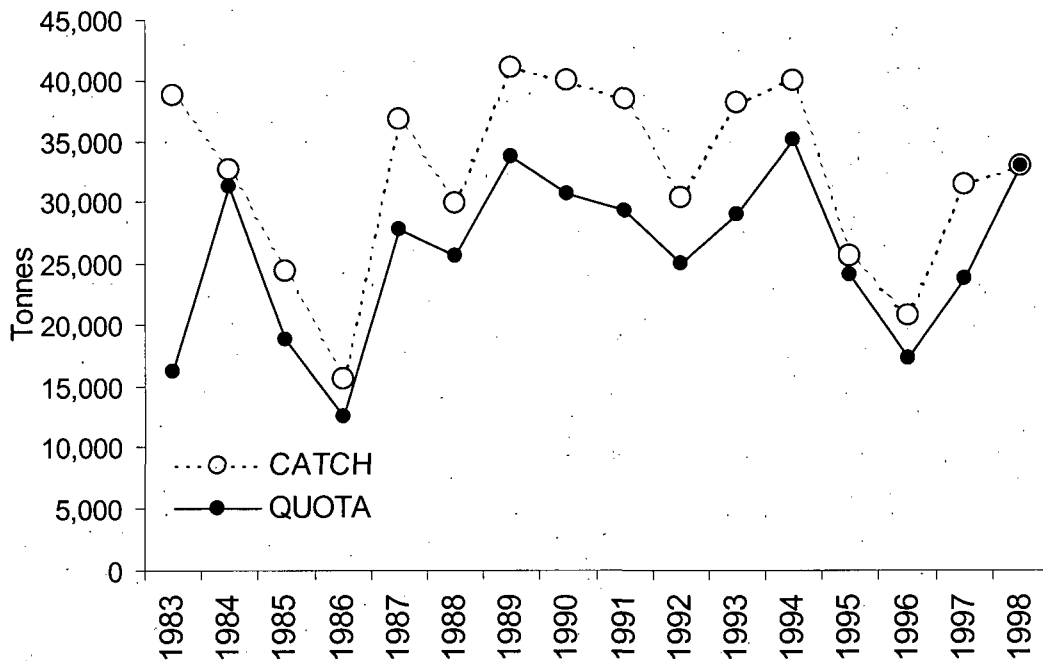


Figure 6.2 British Columbia roe-herring fishery catch vs. quota since inception of fixed harvest rate policy. Note that in 1998 season new harvest control tactics were implemented, vessels being pooled into fishing groups. One vessel from each group fished when directed and catch was shared evenly among licence holders.

Many models that explore effects of fishing on shoaling fish use the starting assumption that shoals are distributed at random. It is well recognised that this is not the case; meso-scale distribution of shoals displays a degree of social organisation that is spatio-temporally linked to local biotic and abiotic factors. However, the random distribution premise is still frequently relied upon due to the lack of ecologically founded, spatially explicit models. For example, Pitcher's (1997) social behaviour model, that presents an alternative to MacCall's (1990) basin hypothesis as a mechanism responsible for producing range-collapse during periods of low stock abundance, assumes initial random distribution pattern of shoals. A more ecologically realistic starting pattern, perhaps where shoals are distributed in tight clusters that are themselves separated, may considerably alter the behaviour of the model and consequently, its results.

Section 6.2 of this chapter details a simulation model, ShoalPattern (programmed in Visual Basic 5.0), that uses predictions from CLUPEX to generate meso-scale distribution patterns of herring shoals; shoal patterns derived from ecological considerations, that may be used as a foundation for harvest models on shoaling fish. In Section 6.3, a conceptual harvest control model is outlined to show the linkage between fish and fishers behaviour, indicating how results from the CLUPEX model can be used to examine the effects of behavioural dynamics on catch rates in herring fisheries, and thus their vulnerability to harvest.

6.2 Generating meso-scale distribution pattern of herring shoals

ShoalPattern uses a re-sampling scheme based on a gamma distribution (whose parameters are taken from empirical data) to generate static displays of shoal structure and meso-scale distribution pattern. Further, by incorporating information on the location and preference of various habitat types, initial distribution patterns are modified. Association of herring with particular habitat types change seasonally and spatially based on rules, in CLUPEX, that express the relationship between herring and its interaction with oceanographic conditions and physical features. Developing on an example from Chapter 5, seasonal changes in shoal structure and meso-scale distribution patterns are visualised. Additionally, comparison is made of how predicted distribution changes according to the re-sampling scheme, model parameterisation and habitat influence. The visualisation of shoals via this graphic interface is intended in the future to be an integral element of the CLUPEX model. An overview of the simulation model and its connection to CLUPEX is shown in Figure 6.3.

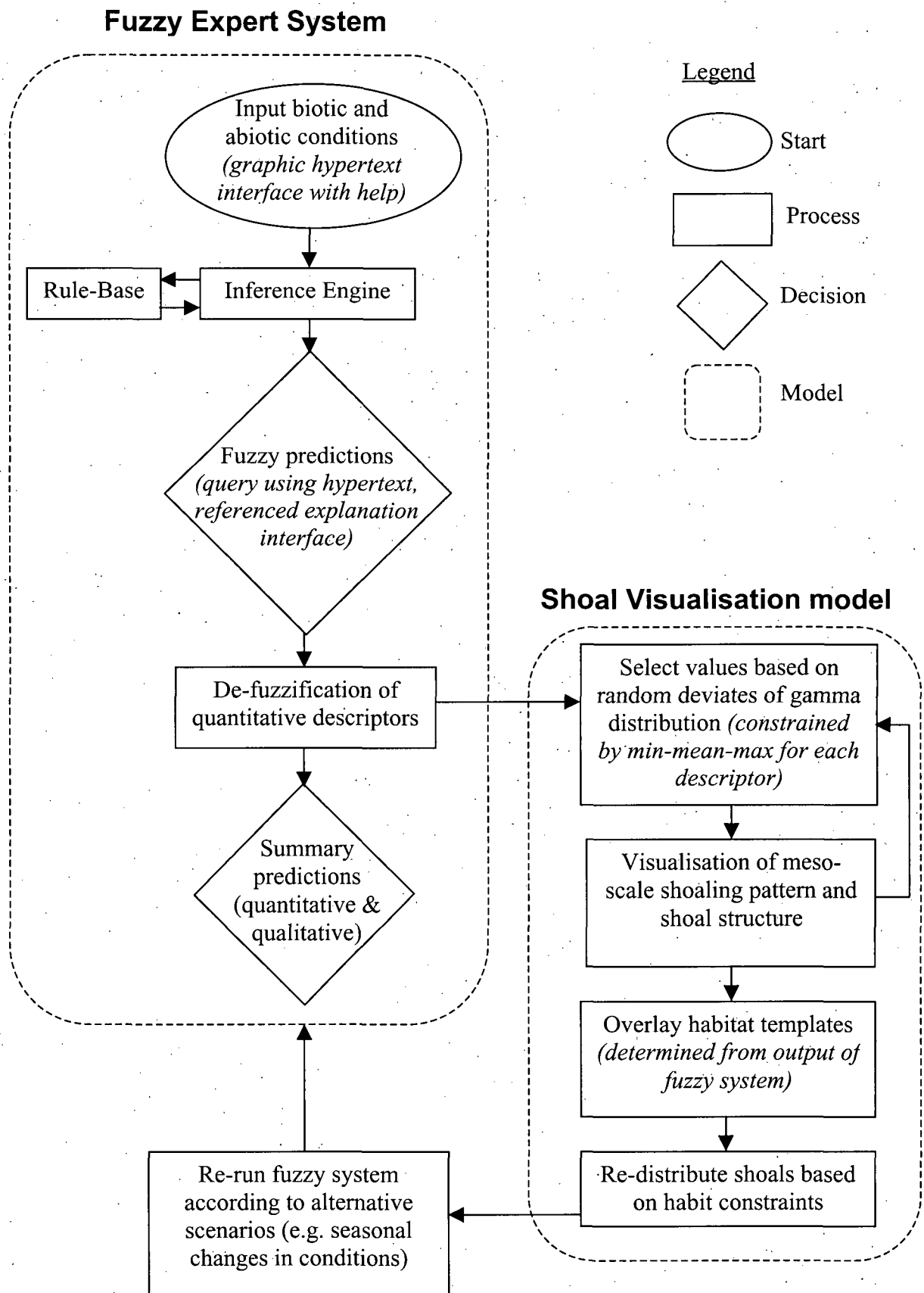


Figure 6.3 Schematic of integrated model combining CLUPEX and ShoalPattern models.

METHODS

Model parameters & specification

In addition to the total biomass (user derived input), the mean and range of 5 quantitative descriptors from the expert system are used to simulate shoaling pattern;

- (i) Shoal size (t) - circular shoals whose radius is proportional to biomass
- (ii) Packing density - represented as an 8 point colour scale (dark red is highest)
- (iii) Relative depth (%) - expressed graphically as a marker on a vertical depth scale.
Surface=0, Bottom = 100
- (iv) mean NND (km) - mean distance to nearest neighbour shoal (Fig 6.4)
- (v) mean \overline{ISD} (km) - mean of the average distance a given shoal to all others (Fig 6.5)

Number of shoals to be plotted is derived from total biomass divided by mean shoal size. The user is given the option of choosing how the total number of schools is distributed between 1-5 clusters. For simplicity, shoals are described as circles.

Each visualisation is scaled relative to the co-ordinates of the furthest outlying shoals to ensure that all shoals appear on the screen; X,Y-scale markers display the distance in km. In addition, a 'free' scale parameter is available for users to zoom in or out to view shoals more clearly. One important consequence of the scaling is that, in the main viewing screen the radius of shoals changes according to scaling. The implication is that whilst for any particular season/scenario simulated, the distribution of shoal size is comparable, that between seasons/scenarios is not. A separate, fixed scale window, can be used to view single clusters in which shoal size is directly comparable between seasons/scenarios.

Key parameters used in generating the meso-scale distribution pattern are mean NND and mean \overline{ISD} . For application in the simulation model, definition of the mean \overline{ISD} is interpreted slightly different from how it is measured from observations (Fig 6.5). In the simulation model, the mean \overline{ISD} represents the distance between clusters; it is the distance from a cluster centre to all other centres (Fig 6.6) and for clarity is renamed here as the Inter-Cluster Distance (ICD). Within clusters, the mean NND is the average distance from a shoal to its nearest neighbouring shoals, viz;

$$\langle ICD \rangle = \frac{1}{N} \sum_{i=1}^{C_{\max}} ICD_i \quad \langle NND \rangle_i = \frac{1}{N} \sum_{j=1}^{s(i)} NND_j \quad \dots(6.1)$$

$i=1, \dots, C_{\max}$ Clusters with centres $c(i)$
 $J=1, \dots, s(i)$ shoals in cluster i

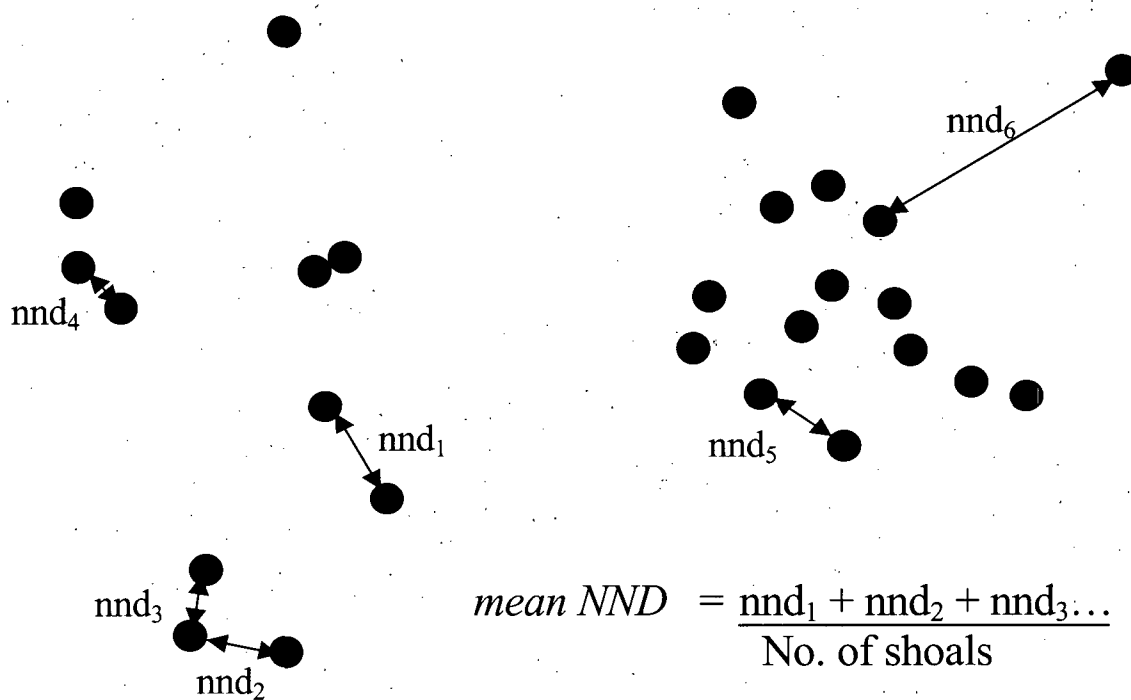


Figure 6.4 Measurement of mean NND based on observation.

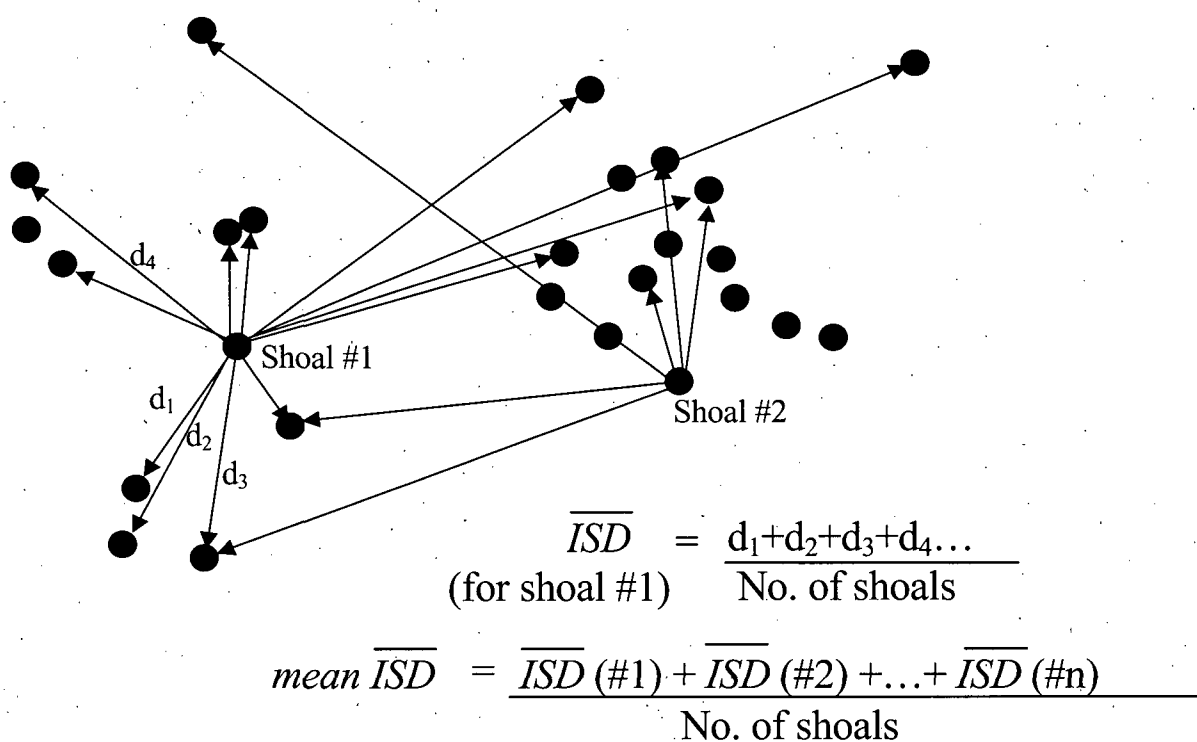


Figure 6.5 Measurement of mean \overline{ISD} based on observation.

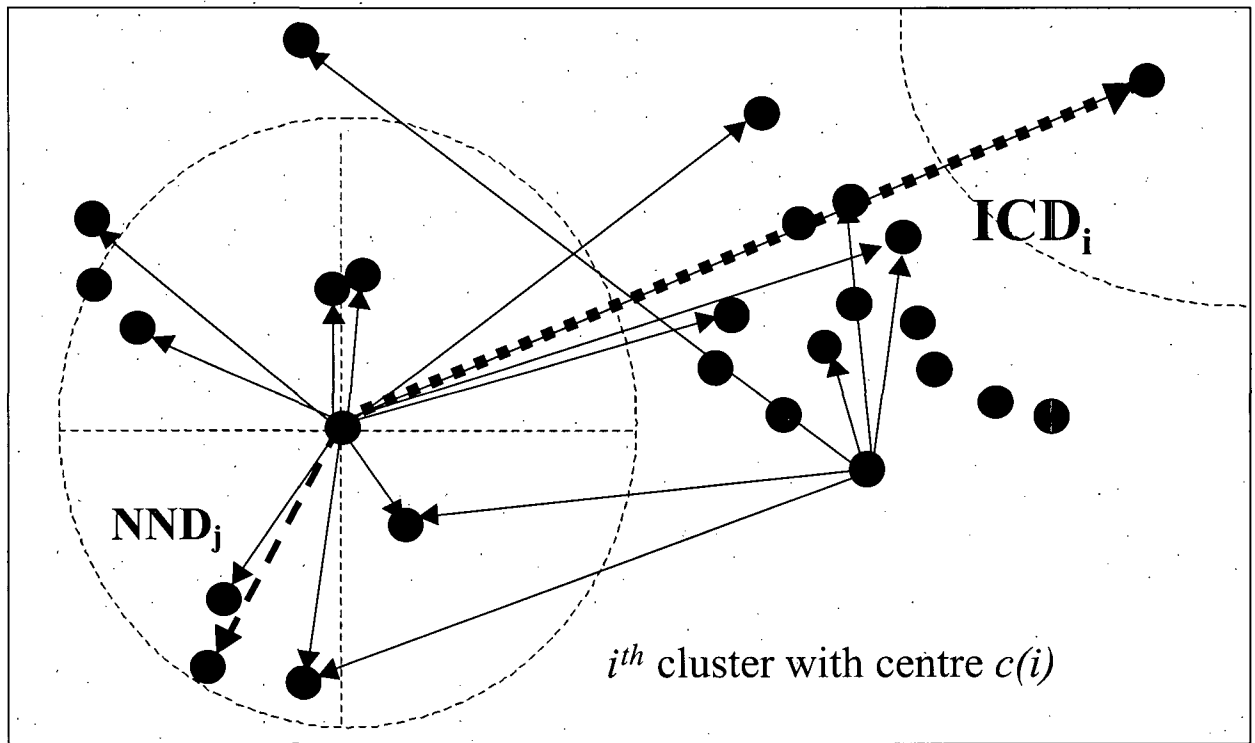


Figure 6.6 Use of NND and ICD parameters in the ShoalPattern model.

While the number of clusters that can be specified in the model is arbitrary, the centres $c(u_o(i), v_o(i))$ currently used for up to a total of five ($i=1, \dots, 5$) shoal clusters are given as,

$$\begin{aligned}
 u_o(1) &= \frac{1}{2} ICD(1) + NND_m & v_o(1) &= u_o(1) \\
 u_o(2) &= \frac{1}{2} ICD(2) + NND_m & v_o(2) &= ICD_m + NND_m \\
 u_o(3) &= \frac{1}{2} ICD(3) + NND_m & v_o(3) &= \frac{3}{2} ICD(3) + NND_m & \dots(6.2) \\
 u_o(4) &= ICD(4) + NND_m & v_o(4) &= u_o(4) \\
 u_o(5) &= ICD(5) + NND_m & v_o(5) &= u_o(5)
 \end{aligned}$$

For the case where the visualisation window has variable scaling, the cluster centres shift between re-sampling and seasonal runs according to the scaling change determined to contain all shoal clusters for viewing. In the alternate case of the fixed scaling window, the shoaling structures can be spanned by adjustment of two slider controls for the (x,y) co-ordinate and

cluster centres appear fixed. To reiterate, shoal sizes are also directly comparable between scenarios within this fixed window.

Re-sampling scheme

The mean and range (min/max) values of the 5 quantitative descriptors are used in random-deviate sampling of gamma distributions to generate values used in plotting shoal structure and distribution. The gamma distribution is characterised by two parameters, scale and shape, whose values are derived from fits to empirical data (Fig 6.7, Table 6.1). The distribution is expressed in terms of a gamma probability density function, $\Gamma(n, \lambda)$, for ($\infty \geq x \geq 0$),

$$f(x, n, \lambda) = \frac{e^{-\lambda x} \lambda^n x^{n-1}}{\Gamma(n)} \quad \Gamma(n, n > 0) = \int_0^{\infty} t^{n-1} e^{-t} dt \quad \dots(6.3)$$

The mean and variance of this distribution are $E(x) = (n/\lambda)$ and $Var(x) = (n/\lambda^2)$ respectively. The distribution is fitted according to a scale ($b = 1/\lambda$) and shape ($c = \text{Int}(n)$) parameters. Random deviates, G , from the distribution are obtained with $U_i \in [0, 1]$ using,

$$G = -b \left(\sum_{i=1}^n \ln(u_i) \right) = -b \ln \left(\prod_{i=1}^n u_i \right) \quad \dots(6.4)$$

The formula is corrected for the mean of the empirical gamma distribution fits.

Unless otherwise specified, generated deviates are restricted to fall within the within (min/max) ranges of descriptor values predicted from the fuzzy expert system. Users can choose to expand the maximum boundary of a gamma distribution for which random deviates are generated, by selecting an error interval that specifies a proportion of the mean used to increase the sampling range.

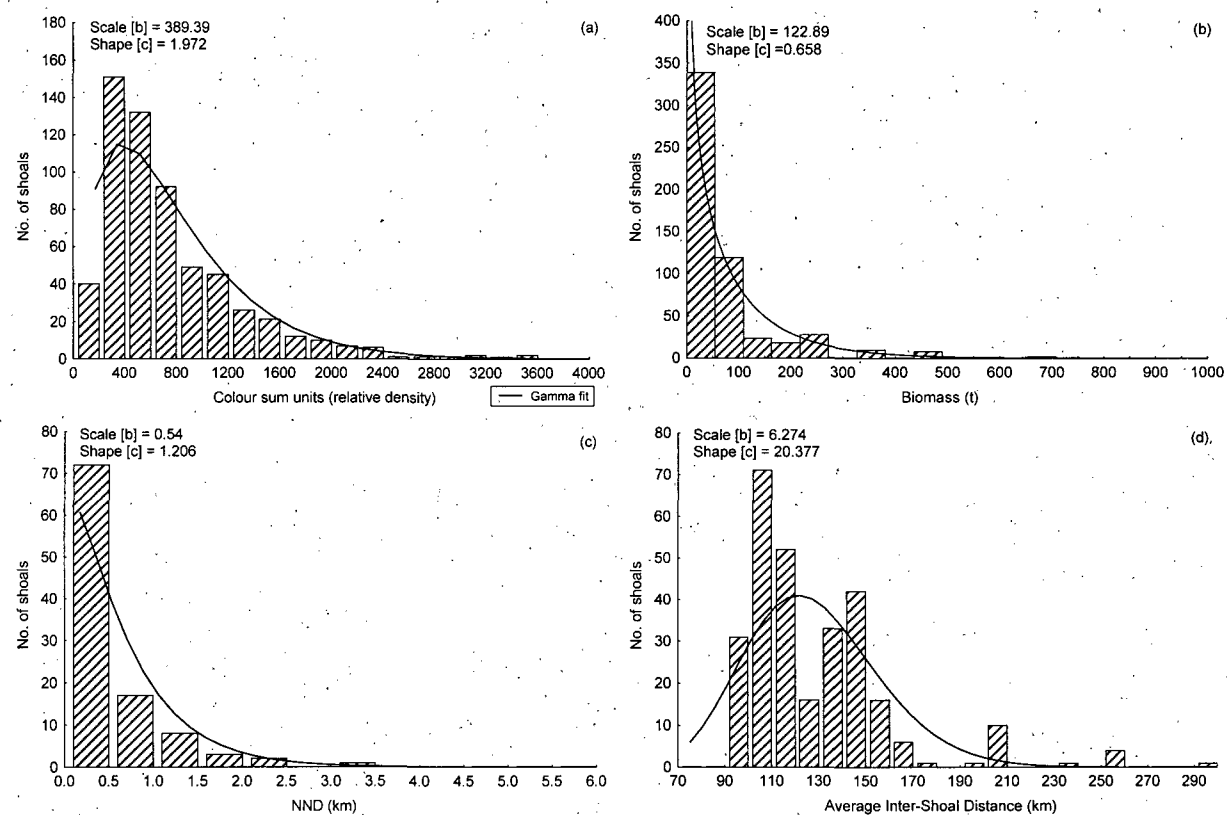


Figure 6.7 Examples of gamma distribution fits to empirical data; (a) Relative density - ocean feeding Norwegian spring spawning herring, (b) Biomass (t) - pre-spawning Pacific herring, Central Coast, (c) NND - pre-spawning Pacific herring, Strait of Georgia, (d) \overline{ISD} - ocean feeding Norwegian spring spawning herring.

Table 6.1 Gamma distribution scale and shape parameters from fits to empirical data.

Descriptor	Data source	Gamma fit parameters	
		Scale [b]	Shape [c]
NND	Norway echosounder	1.644	1.115
	Norway sonar	0.002	617.21
	Strait of Georgia	0.54	1.206
	Central Coast	0.0006	602.11
\overline{ISD}	Norway echosounder	6.274	20.377
	Norway sonar	10.69	1.091
	Strait of Georgia	5.26	8.678
Ln size	Norway echosounder	0.548	9.871
	Strait of Georgia	0.979	4.898
	Central Coast	0.289	11.976
Density	Norway sonar	389.39	1.972
	Central Coast	0.242	18.799
Size	Norway echosounder	1.068	583.06
	Central Coast	0.139	582.12

Additional features under development

Adding habitat structures

When physical (substrate/features) habitats are known to occur, the model includes association of shoals with a non-random (user specified) distribution of habitats. For simplicity, labile oceanographic features such as frontal zones are similarly assumed to be static. The association of shoals with each type depends on season, habitat occurrence, size and preferability. Association with six habitat types are identified by CLUPEX.

1. rock pinnacles/reef structure (RPR) (X,Y, f(R))
 2. frontal zone (FZs) (X,Y)
 3. bluffs of steep sided channels (SSB) (land: (X,Y))
 4. hard bottom with rock outcroppings (HBOT) (X,Y, f(R))
 5. soft bottom with surface irregularities (SBOT) (X,Y, f(R))
 6. passes with high flushing rate and inlets and bays (PIB) (land: (X,Y))
 7. Spawning habitat
- (3,6,7 are land based features and are not presently included in the visualisation model)

Habitat areas of type 'h' are described as circles (radial geometry) with spatial locations (X^h, Y^h). This geometry allows for radial attraction of shoals to the habitat areas without any angular component, i.e. shoals are attracted to a habitat only as a function of the distance to the habitat, it's size and preferability, not as a function of its shape.

The distance between a shoal j located at (x_j, y_j) and a habitat i of type h or radius r^h located at (x_i, y_i) is,

$$D_{ij}^h = \sqrt{(x_i^h - x_j)^2 + (y_i^h - y_j)^2} - r_i^h \quad \dots(6.5)$$

Each habitat of a given type is characterised by the degree to which it attracts a shoal. The attraction strength (AS, denoted by λ) of a habitat is taken as a function of the mean distance between habitats of type 'h' to a shoal, the habitats size (radius), the mean inter-cluster distance and mean nearest neighbour distance. Simply stated, the function ensures that for a given habitat type, bigger habitats pull harder and, the closer a shoal is to a habitat, the stronger its attraction.

$$\lambda_{ji}^h = \lambda_{ji}^h \left(\overline{IHD}^h, r^h, \overline{ICD}, \overline{NND} \right) \quad \dots(6.6)$$

A shoal j within a cluster w is then attracted to a given habitat according to an iterative scheme for the (n+1)th iteration (n=1,...,n_{max}).

To represent differences in 'suitability' (denoted by η) between habitat types, a fixed value specific to each habitat type can be assigned in the attraction function. For example, for inverse square attraction, $\eta=2$. The suitability parameter is important when more than one habitat is present. Where soft bottom and hard bottom habitats occur together, herring are assumed to prefer soft bottom substrate.

Evaluation and sensitivity criteria

The behaviour and relationship of spatial scaling between shoals and clusters, are estimated from each static distribution according to the re-sampling scheme. Sensitivity analysis can be performed by using a fuzzy clustering procedure to compare variation in distributions. Specifically, 3 parameters can be used to compare the stability of the shoal patterns across interval re-sampling; total variation of data set to the cluster partitions, compactness and separation validity function.

RESULTS

Runs of ShoalPattern are used to examine 3 points: (i) seasonal changes in the distribution pattern of Pacific herring; (ii) effect of error interval on shoaling pattern (iii) effects of re-sampling gamma distributions. Model settings used for all simulations below include; scaling = 30; NND error int.= 30; ICD error int.= 0; Packing density error int.= 0; Shoal size error int.= 0; # of clusters = 4, with number of shoals evenly distributed amongst clusters; gamma distribution parameters (Table 6.2).

Table 6.2 Gamma distribution parameters used for seasonal simulations.

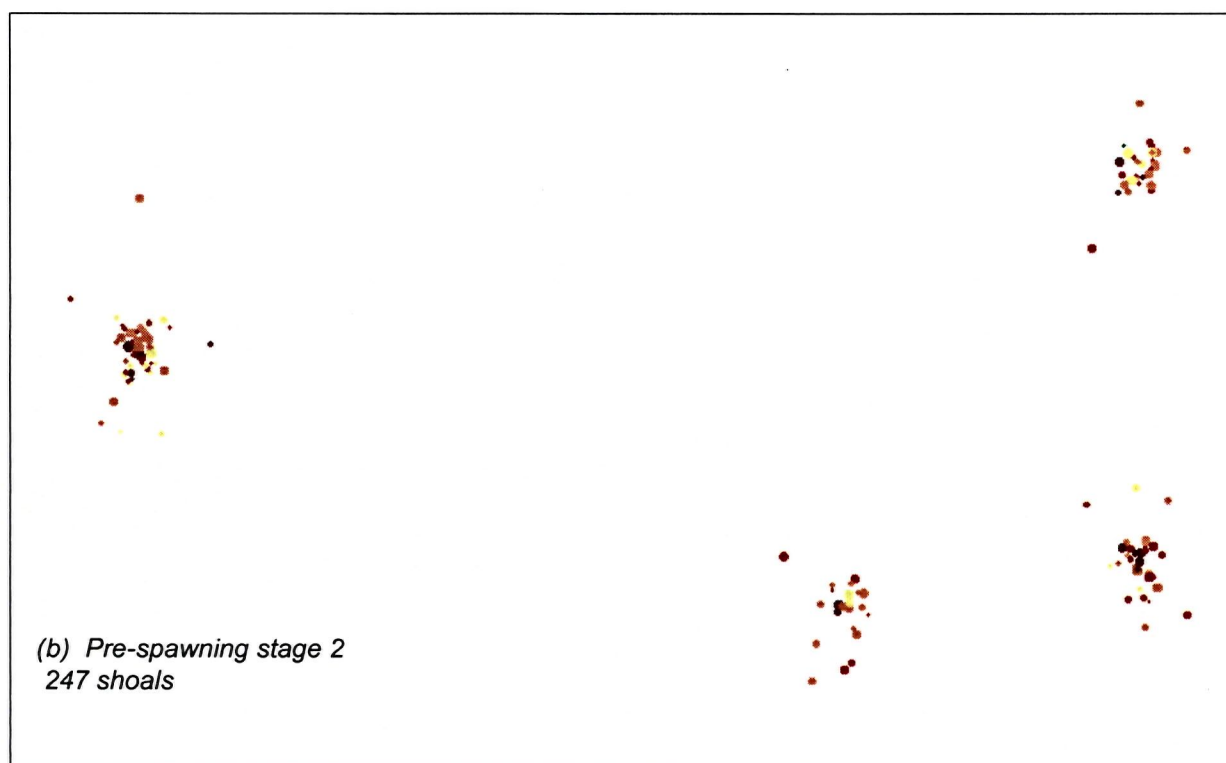
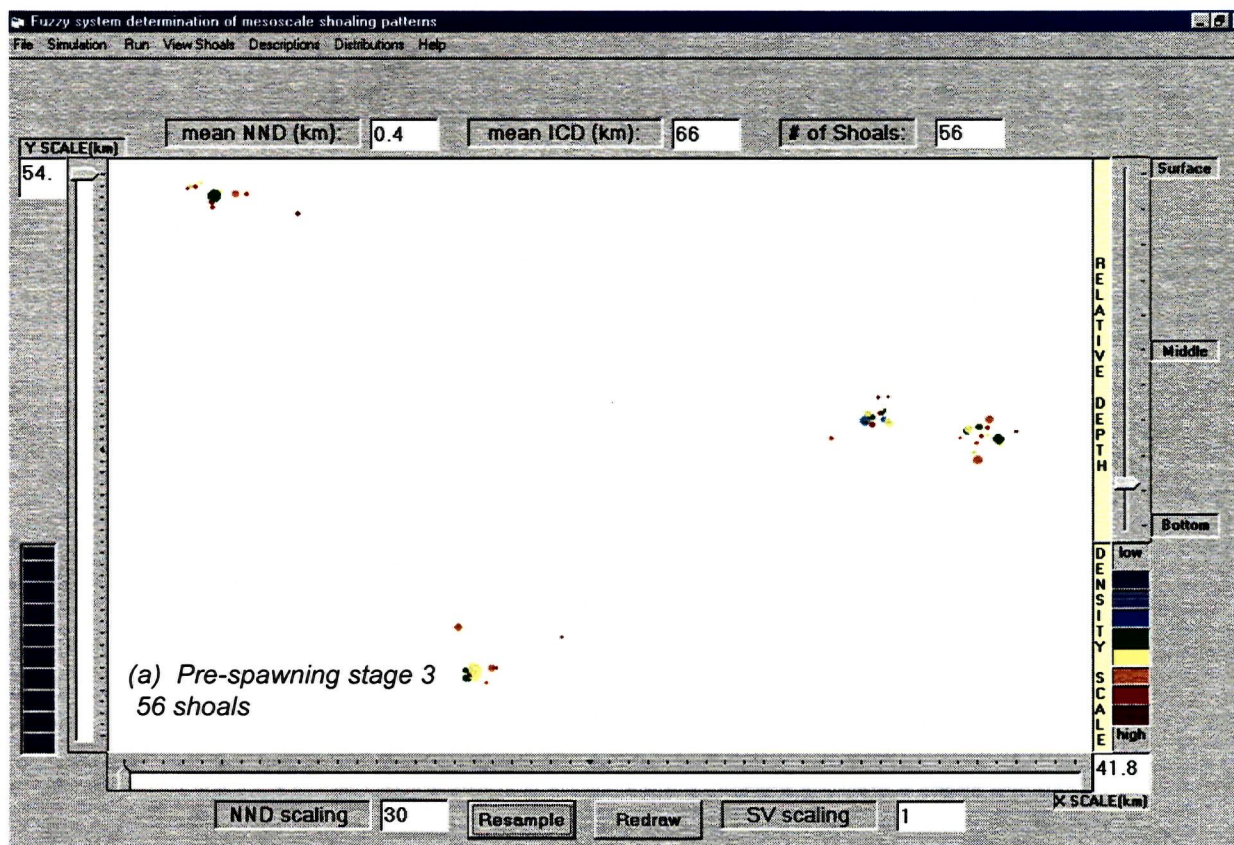
	Scale (b)	Shape (c)
For: Pre-spawning, spawning, immediate post spawn and overwintering:		
Shoal size	600	1
Density	0.242	18.79
NND	0.44	0.864
ICD	5.39	9.01
For: Offshore migration, ocean feeding, onshore-migration		
Shoal size	1028	0.605
Density	0.242	18.799
NND	1.644	1.115
ICD	6.274	20.377

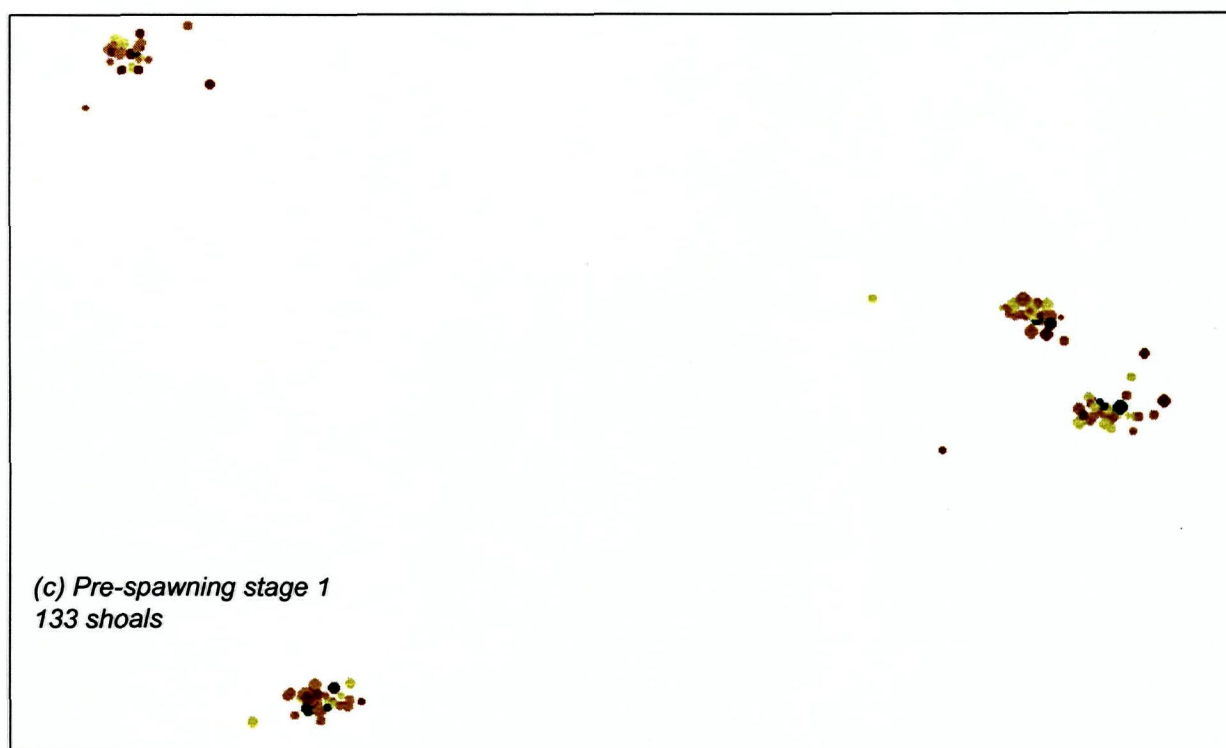
Seasonal changes in shoal distribution pattern

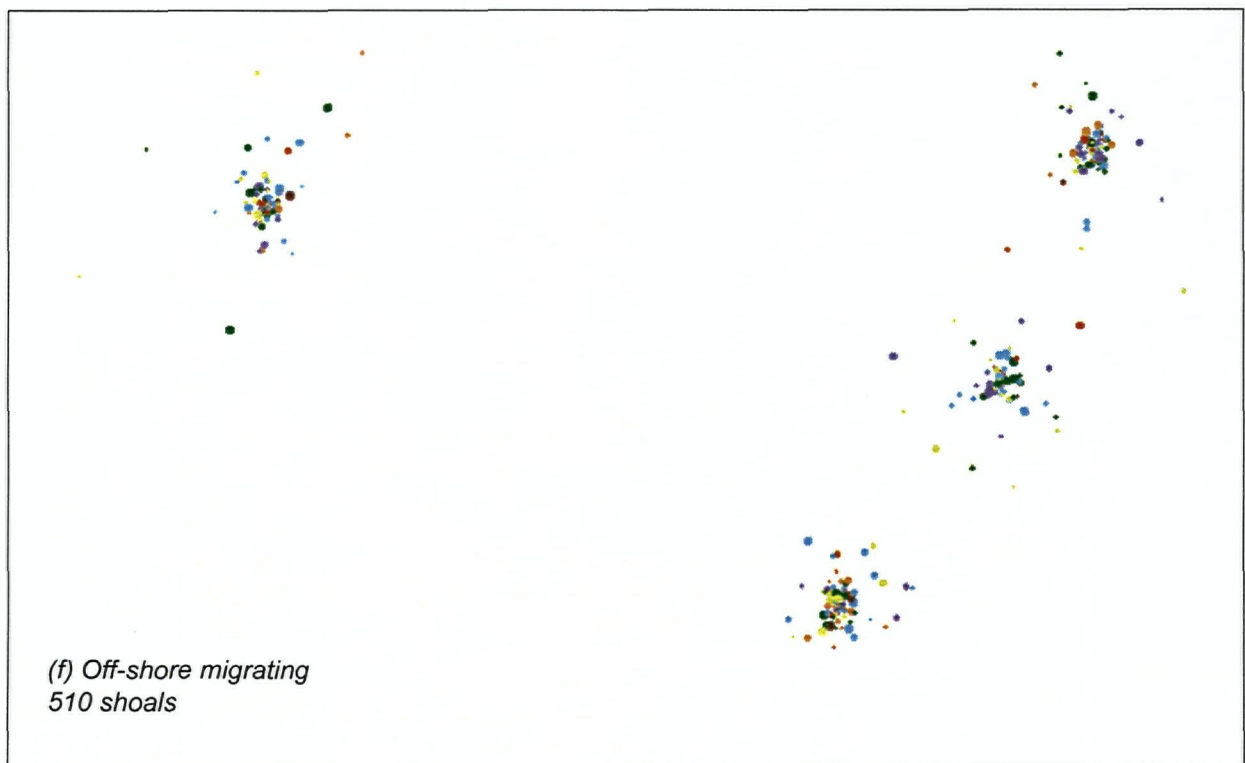
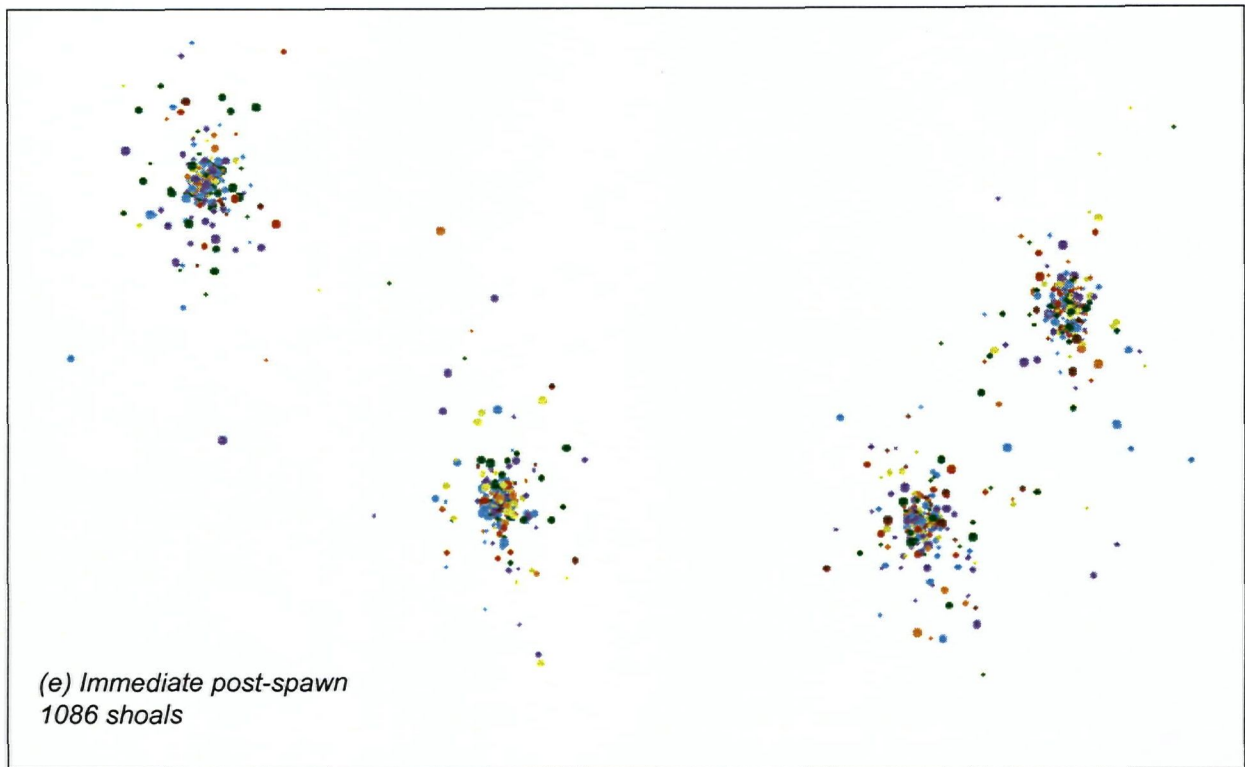
Using the same input data from the example in Chapter 5 (Table A 5.3), CLUPEX is used generate output parameters for seasonal dynamics of Pacific herring (Table 6.3) from which static meso-scale shoaling distribution are visualised (Fig 6.8).

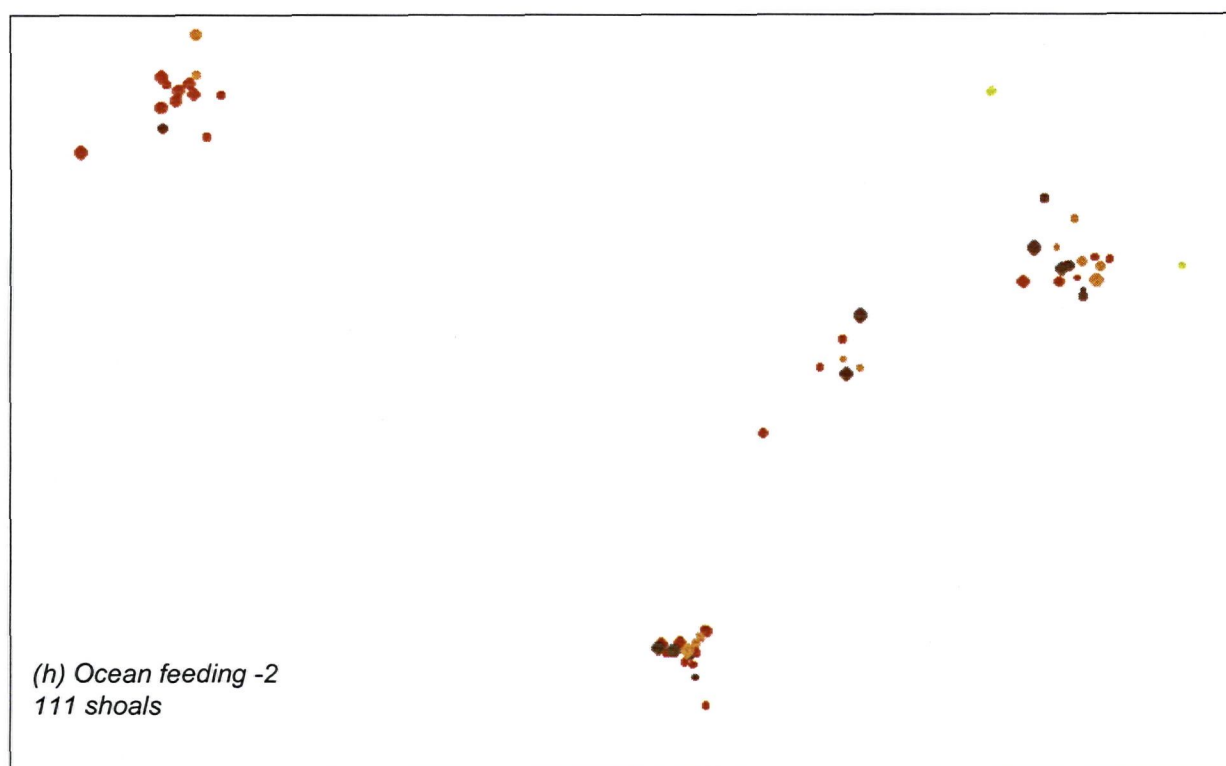
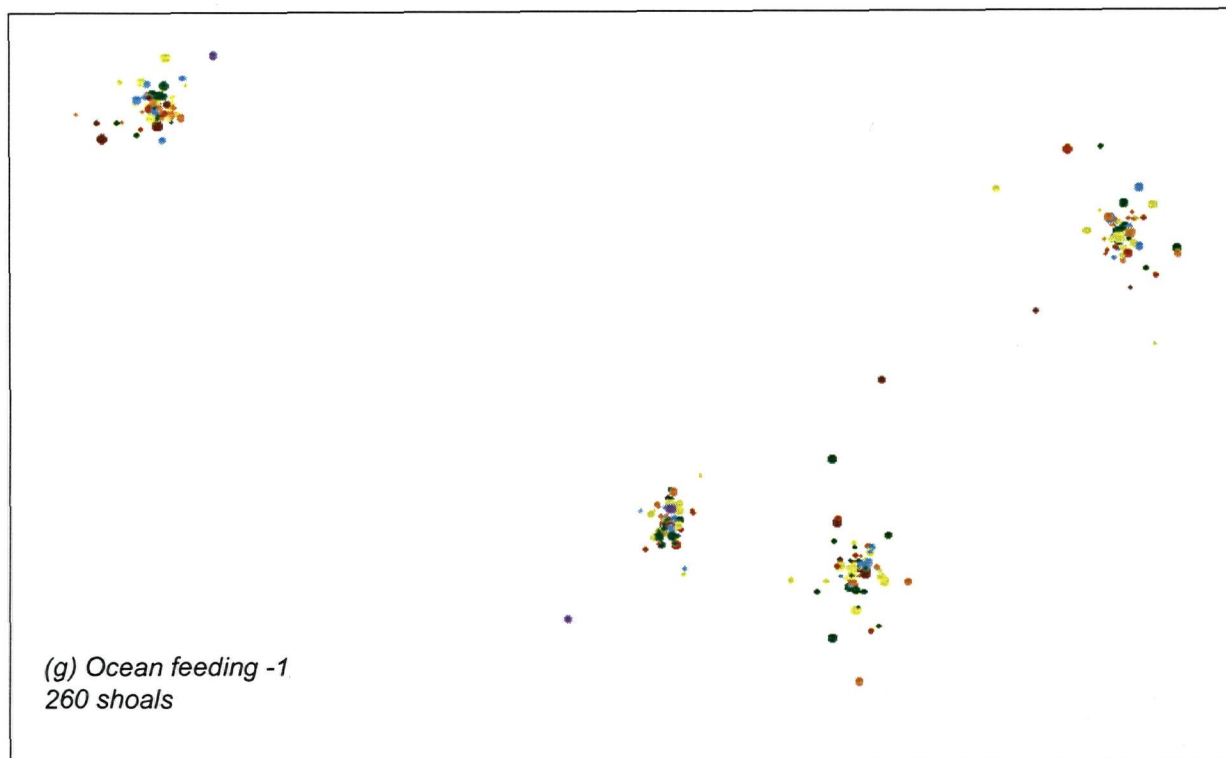
Table 6.3 Quantitative descriptors of seasonal changes in Pacific herring used in the visualisation model.

Season	Pre-spawning 3 to 2	2 to 1	1	Spawning	Immediate Post-spawn	Off-shore-migration	Ocean feeding 1	2	3	On-shore migration	Overwintering
inputstock	50000	50000	50000	50000	50000	50000	50000	50000	50000	50000	50000
shoalsize	890	202	374	371	46	98	192	449	250	102	1391
shoalsizemin	264	72	152	108	12	23	61	189	92	24	403
shoalsizemax	3197	374	664	1143	97	198	368	786	458	206	5300
packden	3.4	6.7	6.7	18.1	0.9	1.8	3.2	8	4.6	1.8	9.1
packdenmin	1.1	1.9	1.9	6	0.3	0.6	1	2.2	1.4	0.7	2.4
packdenmax	10.1	17.9	17.9	33.7	2.4	5.3	9.5	21.2	12.9	5.5	24.1
shoaldepth	88	79	38	25	25	72	72	72	73	72	82
shoaldepthmin	75	65	18	5	5	57	57	57	58	57	68
shoaldepthmax	98	91	55	40	40	87	87	86	87	86	93
speed	0.75	0.75	0.69	0.75	1.12	0.74	0.74	0.76	0.75	0.74	0.29
speedmin	0.3	0.3	0.27	0.3	0.65	0.3	0.3	0.32	0.3	0.3	0.08
speedmax	1.3	1.3	1.21	1.3	1.89	1.29	1.29	1.32	1.29	1.29	0.56
dyntend	9	9	9	9	9	9	10	11	10	9	7
dyntendmin	5	5	5	5	5	5	6	7	6	5	2
dyntendmax	14	13	14	14	14	14	14	17	16	14	11
catchease	31	39	39	39	19	25	25	25	25	25	25
catcheasemin	15	24	24	24	7	10	10	10	10	10	10
catcheasemax	47	56	56	56	33	40	40	40	40	40	40
rockreef	0	0	0	0	0	0	0	0	0	0	0
ISDmav	66	59	52	52	51	66	66	51	59	66	63
ISDmavmin	41	34	28	28	28	41	41	27	34	41	38
ISDmavmax	106	94	86	86	83	107	107	84	93	107	100
NNDm	0.4	0.5	0.4	0.4	0.8	0.7	0.6	0.4	0.6	0.7	0.5
NNDmmin	0.1	0.2	0.1	0.1	0.3	0.3	0.2	0.1	0.2	0.3	0.2
NNDmmax	1	1.1	1	1	1.6	1.5	1.2	0.9	1.2	1.5	1
frontal	0	0	0	0	0	0	2	2	2	0	0
steepbluff	2	2	2	0	0	0	0	0	0	0	2
hardbot	0	0	0	0	0	0	0	0	0	0	0
softbot	2	2	2	0	0	0	0	0	0	0	2
passbay	2	2	2	0	0	0	0	0	0	0	2
spawnsub	0	0	0	2	0	0	0	0	0	0	0











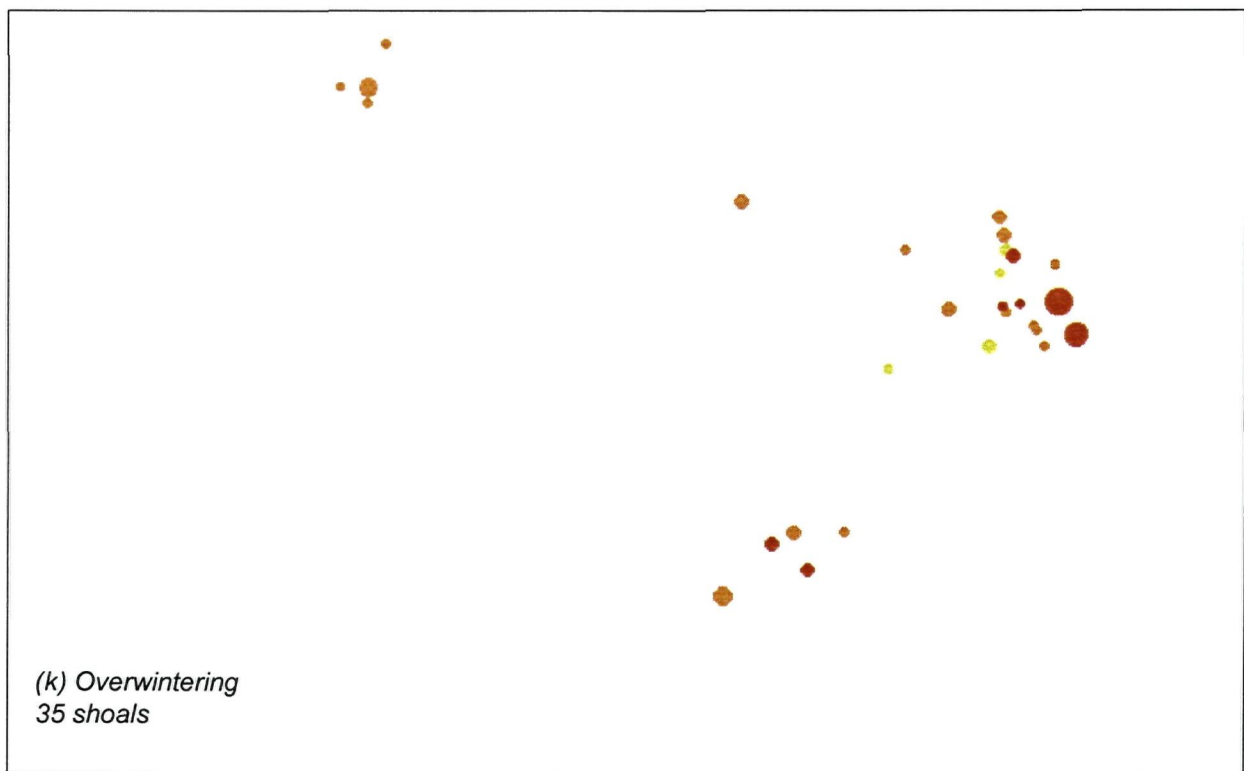


Figure 6.8 Visualisations of predicted seasonal structure and meso-scale distribution of herring shoals (see Table 2.2 for parameterisations of ShoalPattern runs). Four clusters are used in each visualisation and the total number of shoals is evenly distributed amongst clusters. (a) displays ShoalPattern screen.

Visualisation of predicted seasonal changes in the distribution pattern of Pacific herring shoals captures the main features that have previously been observed in the wild, notably:

- i) Early pre-spawners often form aggregations similar to those observed during overwintering; a distribution typified by several very large medium density shoals holding the majority of biomass (Fig 6.8a). Stage 2 of pre-spawning sees clusters dispersing as individual shoals break down in to smaller, more densely packed, mobile shoals (Fig 6.8b), before re-aggregating near the spawning grounds (Fig 6.8c). Spawning shoals typically form high density layers aggregated in shallow water (Fig 6.8d, Table 6.3) (Hay, 1985).
- ii) Spawned out herring migrate away from the spawning grounds, swimming fast and high in the water column (Table 6.3) in very small and small, low density shoals (Fig 6.8e) (Hourston and Haegele, 1980; Nøttestad et al. 1996; Axelsen, 1997). The distribution pattern is considerably more dispersed than that of pre-spawners, although a general structure is still apparent.
- iii) Migrating herring form polarised schools and are typically small in size (e.g. 100t). Although packing density is higher for fast moving shoals (Table 6.3) (Pitcher and Partridge, 1979) it may vary depending on local conditions; under the conditions specified here (Table A 5.3), low-medium density shoals are predicted (Fig 6.8 f & j).

During migration, herring may swim deep in the water column utilising favourable currents (Fernö et al. 1998; Nøttestad et al. 1999).

- iv) Ocean feeding shoals are smaller than overwintering shoals (Table 6.3) (Buerkle and Stephenson, 1990). Changes in the predicted distribution pattern between 3 discrete periods (Fig 6.8 g,h,i) result from behavioural trade-offs occurring in relation to changing feeding opportunities and predation risk (Table A 5.3). During period 1, food is abundant and predator abundance low; herring form smaller shoals more loosely clustered to capitalise on feeding opportunities (Fig 6.8g). Increased predation risk relative to feeding in period 2 (Fig 6.8h) results in more intense clustering, formation of larger shoals (2 times on average, Table 6.3) and dense packing of individuals within shoals. NND and ICD are reduced resulting in a tighter pattern of aggregation among all shoals. In period 3, food is moderately abundant and predators common. The decreased risk of predation relative to feeding opportunity allows for smaller shoal size (Table 6.3) and increased distance among neighbours. Since risk of predation is higher than in period 1, shoals are more tightly clustered and densely packed.
- v) Since survival during overwintering is largely an exercise in predator avoidance and energy conservation (Huse and Ona, 1996), herring generally form very large aggregations of one or several shoals (McCarter et al. 1994). In the example predicted here (Fig 6.8k) there are 35 shoals holding 50,000t. For comparison with other runs, the shoals were distributed in 4 clusters, although one cluster may be more realistic. In each cluster, the majority of the biomass is contained in 1 or two very large shoals (mean shoal size is 1391t).

An additional point worth emphasising is that a high occurrence of small shoals relative to large shoals is predicted for all seasonal phases. This simply reflects the skewed distribution of shoal sizes observed in the wild (Mackinson, Chapter 2) and is assumed here under parameterisation of the gamma distribution.

Effects of error-interval on shoaling pattern

Changing the error interval modifies the maximum range from which random deviates can be selected from the gamma distributions. Increasing the error value extends the tails of the distribution for selection of values by random sampling. In the example provided in Fig 6.9, the error value for NND distribution is increased from zero to fifty. From zero to thirty, an increasing spread in the distribution is observed. Beyond thirty, there is no apparent difference; a result that occurs because the boundary has been extended beyond the maximum tail of the gamma distribution specified for NND.

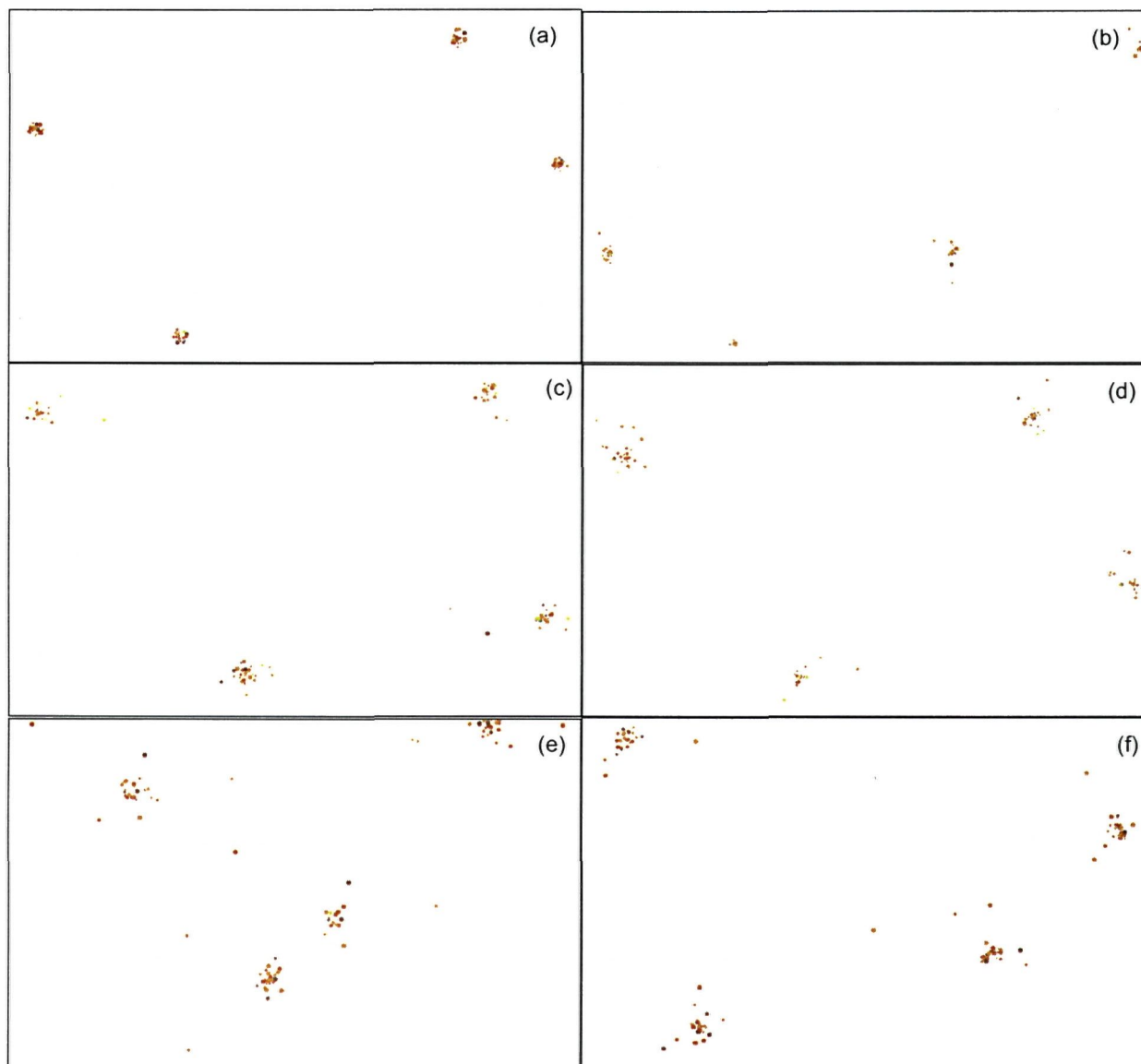


Figure 6.9 Effects of error interval on shoaling pattern (a) error int. = 0; (b) error int. = 5; (c) error int. = 15; (d) error int. = 25; (e) error int. = 30; (f) error int. = 50.

Effects of re-sampling gamma distributions

To qualitatively examine the effects of re-sampling gamma distributions, one specific scenario (overwintering Pacific herring) was chosen for re-sampling (Fig 6.10). In each panel of Fig 6.10, the mean shoal size, NND, ICD, and packing density remain the same. The re-sampled distributions emphasise that even for one specific scenario, considerable variation between predicted distributions can occur.

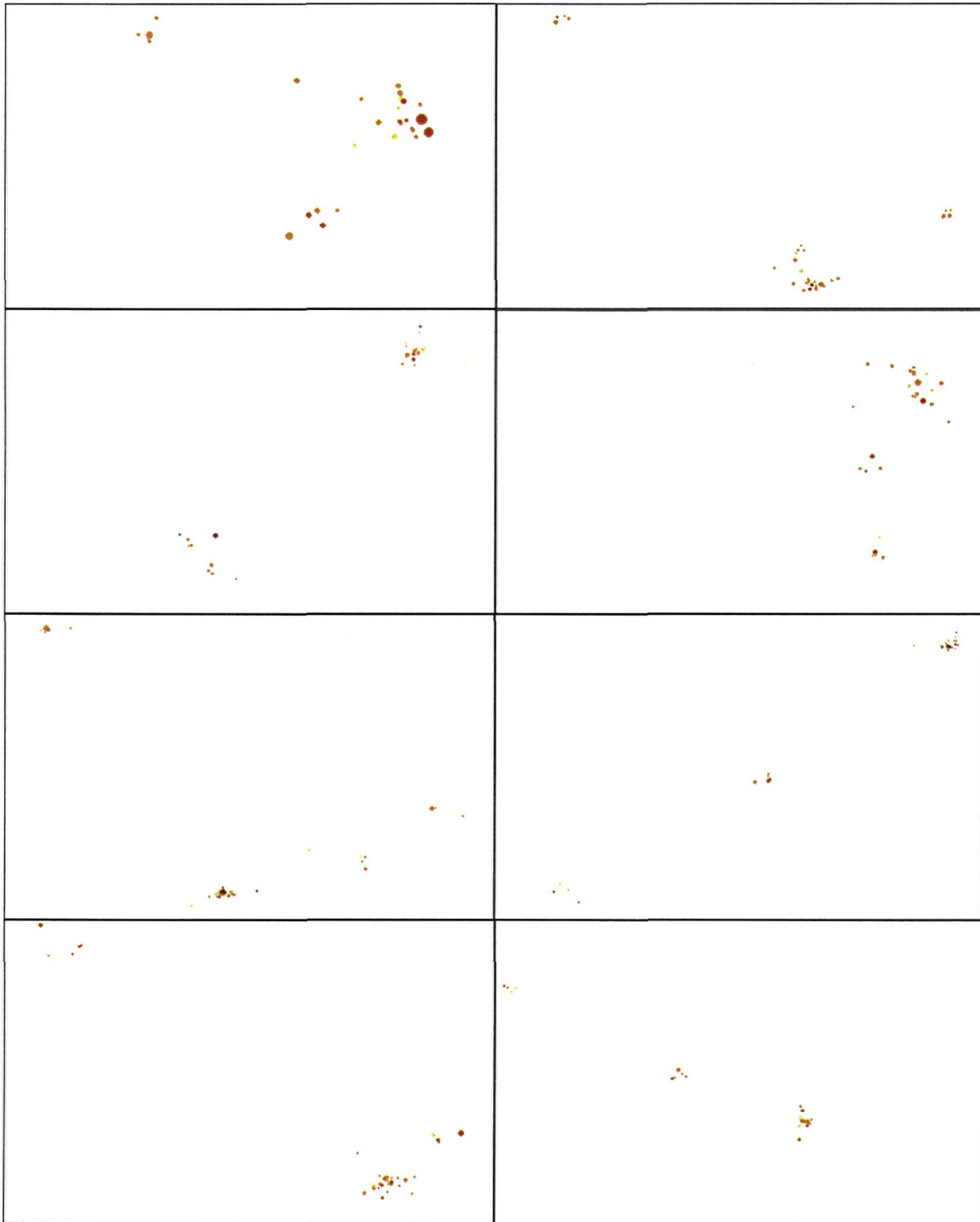


Figure 6.10 Shoal patterns from re-sampling gamma distributions. Each panel displays a single run for which random deviates are taken from each of four gamma distributions being sampled; shoal size, packing density, NND, ICD.

DISCUSSION

The relatively simple measures, mean NND and mean \overline{ISD} provide quantitative description of observed meso-scale distribution pattern of shoals and, as applied here, with few assumptions can be used in to generate predicted distribution patterns of shoals; important foundations to understanding and exploring the importance of spatial distribution in fisheries management (see section 6.3). To my knowledge, no other authors have modelled shoaling distribution based directly on ecological foundations; either non-random distributions are assumed or some other method is used to generate aggregation, such as cellular automata models (e.g. Millischer and Gascuel, 1998).

Examination of seasonal changes in the structure and meso-scale shoaling distribution patterns of Pacific herring highlight the main features previously observed in the wild. There are few empirical studies with which to directly compare the predicted spatial distributions, other than those detailed in this thesis (Chapter 2), and integral to the predictions themselves. Treatment of spatial clustering in shoaling pelagic fish by other authors has resulted in discrete definitions based on 'linear' clusters; partly a consequence of shoals being located consecutively on 'linear' acoustic cruise tracks (e.g. Petitgas and Samb, 1998; Soria et al. 1998). Application of a meso-scale mapping protocol, like that detailed in Chapter 2, may help elucidate features of shoal clusters that will enable us to better model such distributions in the future.

Through parameterisation of gamma distributions, generation of shoaling pattern by the ShoalPattern model is closely tied to empirical data and thus points to the need for further studies on meso-scale distribution patterns. Where empirical data exists, gamma distribution parameters are varied by season in predictions made here, in an attempt to more closely model the distribution observed in the field. Clearly, improved seasonal (and also regional) measurements of shoal distribution parameters (NND and \overline{ISD}) would improve spatial predictions of CLUPEX and ShoalPattern models.

When applied to the distribution of NND, the error interval acts as a cluster intensity index. Lower intervals constrain the distribution and produce tighter clusters, whilst high intervals open the sampling distribution, and thus spread the shoals. Currently, distribution intervals are set by the maximum and minimum values for each quantitative descriptor output from CLUPEX. With improved empirical data on distributions of these descriptive parameters it might be more appropriate to set intervals according to observed values. Similar to gamma distribution parameters (scale and shape), the interval may change according to seasonal or regional differences, thus providing the ability to tune the model to more specific situations.

The re-sampling scheme of the model is a key feature that allows examination of potential variations in shoals distribution pattern that occur for a specific suite of variables input to CLUPEX. From the qualitative analysis of the variation in distribution patterns for overwintering

Pacific herring, we see how potentially many structural organisations may be appropriate for any situation. Such flexibility/ variation could be advantageous and might arise in herring shoals simply as consequence of their behavioural plasticity. GEOSPACE group (1993) comment "...it is impossible to consider spatial structures of shoals as being exclusively produced by environmental constraints. According to the ethology of the populations, several spatial structures may be the answer to a single hydrological or tropic organisation".

A noticeable feature of the visualisations is that broadly speaking, when we assume four clusters for each period, the 'pattern' of clustering does not change markedly. Whilst part of this is dependent on the organisation scheme for positions set for clusters, we are at present (with lack of other evidence) left to consider whether or not such seasonal patterns might exist? Do clusters maintain integrity by season? Pitcher and Carvalho (unpublished) have evidence suggesting that individual anchovy within shoals are more closely related than those between shoals. Similar relatedness of shoals within clusters might support the notion of integrity. How and when might such clusters best be identified? Perhaps during the pre-spawning aggregation of shoals? A striking question that would have to be answered is as to how cluster integrity could be maintained during periods of stock mixing such as ocean feeding periods?

Members of a cluster..... 'to be or not to be?' That is the question.

'to be AND not to be!' That is the fuzzy answer.

Whether or not shoals belong to a cluster cannot be approached by assuming break points; in OR out, yes OR no, member OR not? (see for example of break points: Petitgas and Samb, 1998; Soria et al. 1998). Take for example any of the figures where one cluster overlaps another: which shoals who belong to what cluster? The answer is that individual shoals belong to both clusters. The key is partial membership; they belong to each cluster to a certain degree. This is where fuzzy logic, and fuzzy clustering in particular can provide considerable insights for analysis and description of shoaling fish. Standard K-means clustering algorithms (Bishop, 1995) require that the number of cluster be specified before an analysis is run. Such methods can be applied where clusters are obvious (but why bother using algorithm if they are clearly visible?), but are not appropriate where we wish to search for clusters in the data. Using an algorithm to distinguish clusters, particularly when points are not necessarily easily defined in one cluster or another, would provide considerable advantage to analysis of shoaling pattern observed in the wild. Recently, Mackinson et al. (1999) used such an algorithm to define clusters in stock-recruitment data. The algorithm is a modified fuzzy c-means clustering algorithm (Dunn, 1974; Bezdek et al. 1987) programmed by N. Newlands. In the future, perhaps the approach could be adapted for use in the ShoalPattern model. Fuzzy cluster analysis of shoal observations might be used provide a guide for choosing appropriate numbers of clusters for different seasons. Moreover, rather than arbitrarily defining the number of shoals for a set number of clusters, shoals might be assigned degrees of membership to more than one cluster. The routine would serve to extend comparisons between CLUPEX predictions and actual empirical shoal distributions obtained using research/ fishing vessels, aerial, remote-sensing or satellite direct-observational methods (Lutcavage et al.

1998). The application of fuzzy principles to the study of shoaling shows remarkable promise. Mackinson and Newlands have already discussed key fuzzy concepts relating individual behaviour to shoaling dynamics, and is currently under study by Newlands for application to modelling Atlantic blue fin tuna (*Thunnus thynnus*) schools.

6.2 Implications for harvest control in fisheries on shoaling species

When space-time restrictions are used to limit effort, the catch rate will depend on both the abundance and catchability of the fish in the area, and how the fishing vessels respond to this abundance (Hilborn, 1986). To answer the necessary questions, 'where, when and how many?' considerations of the behavioural dynamics of fish and fishing fleets must be recognised as integral parts of the effectiveness of a tactic. A brief theoretical treatment is given here to highlight how results from CLUPEX may be used in the formulation of a simple fishing model to examine the impacts of shoal dynamics and fishing fleet dynamics on harvest control in herring fisheries.

SIMPLE CONCEPTUAL MODEL OF A HERRING SEINE FISHERY

Behaviour of fishers

Here a simplistic model of fisher behaviour is developed based on the time budget that a typical seine vessel allocates to travelling, searching, setting and handling (see Hilborn and Walters, 1992). Assuming that vessels are already on the fishing ground, travel time can be excluded; and the total time budget allocated to fishing T is;

$$T = \text{Time spent searching } (T_s) + [\text{Time spent setting} + \text{Time spent handling } (T_h)] \quad \dots(6.7)$$

Searching: assume a typical vessel searches at speed, s (kmh^{-1}) and detects shoals at a width w (km) on each side of the vessel, and that any shoal closer than w km from the vessel will be seen, and those beyond are missed. (In reality there is a probability of detection that diminishes with distance from the vessel, but this can be translated in to an effective sweep width, w). The vessel therefore searches and area A per hour of searching;

$$A = s \times w \times 2 \text{ (km}^2\text{)} \quad \dots(6.8)$$

Suppose that if a shoal is seen there is probability p that the skipper will chose to set on it (I will return to this later), and for any vessel, the combined set and handling time takes h hours depending on the size of the shoal. For herring seines it might be reasonable to assume a fixed

set time of half an hour and a linear increase in handling time with mean shoal size c , where a 500t school takes 24 hours to pump in to packing vessels;

$$h = 0.5 + (0.05 \times c) \quad \dots(6.9)$$

Thus, assuming shoals are of the same average size c and when a set is made, all the shoal is caught, each set takes an average of c tonnes. The number of shoals per km^2 is N .

According to the above assumptions and definitions it is possible to predict the sets made by a vessel S and its catch rate ($U = Sc$), using the time budget (eq. 1) First, the number of sets that a typical fishing boat will make during fishing time T is the probability of setting times the encounter rate ($A \times N$) multiplied by time spent searching;

$$S = pANT_s \quad \dots(6.10)$$

$$\text{Time spent searching is; } T_s = \frac{S}{pAN} \text{ and,} \quad \dots(6.11)$$

$$\text{time spent handling is; } T_h = hS \quad \dots(6.12)$$

Substituting the expressions in to the time budget (eq. 1) the total time spent fishing is;

$$T = hS + \frac{S}{pAN} \quad \dots(6.13)$$

and the catch rate per vessel in tonnes per total fishing hour U is expressed as a functional response by vessels to the distribution and density of schools. This relationship is often referred to as Holling's Disc equation (Holling, 1959):

$$U = \frac{TpANc}{1 + hpAN} \quad \dots(6.14)$$

Total catch (C) is catch rate multiplied by effort (E) (in this case number of vessels),

$$C = UE \quad \dots(6.15)$$

More detailed, functional approaches to harvesting efficiency are considered by Paloheimo and Dickie (1964), Clark and Mangel (1979), Mangel (1982). Profit maximising behaviour of fishermen in harvest tactic models is explored by Sampson (1990, 1991, 1992).

Herring behaviour

Behavioural responses to local biotic and abiotic conditions may result in spatio-temporal changes in the structure and distribution of herring shoals, thus influencing both *availability* of shoals to capture and the *efficiency* with which shoals are caught. In this simple model, changes in number and distribution pattern affects the number of shoals N in the fishing area, whilst changes in shoal depth, size, density and speed influence the probability p that a skipper will choose to set on a shoal.

Using quantitative predictions from the CLUPEX model, the effect of behavioural dynamics on catch rate could be examined. Even though functional relationships that describe the effects of shoal structure and distribution on probability of making a set are not known, it is possible to use an exploratory approach by developing easily modified rules in a fuzzy expert system that express the possible nature of such relationships. Potential linkages between shoaling and fishing dynamics are expressed in a conceptual model that can be examined in more detail in the future (Fig 6.11).

Millischer and Gascuel (1998) have developed an individual based harvest control model that examines the impacts of various scales of shoaling fish aggregation patterns on fishing success. However, unlike the CLUPEX model, their modelling of fish distribution is not founded on ecological conditions but rather is generated using various methods producing different levels of spatial aggregation.

Evaluation of model fishery

A useful evaluation tool that summarises the necessary information on spatial distribution and abundance is the performance curve. A performance curve specifies the cumulative proportion of catch or CPUE as a function of time in a specific locality (Mundy et al. 1985) (Fig 6.12). The slope of the performance curve is a measure of the catch rate. Performance curves could be used as a convenient way to evaluate the consequences changing spatial and temporal distribution and structure of shoals on fishing. For each spatial configuration of shoals the cumulative catch or CPUE may be plotted over time. The aim is to identify shoaling pattern or perhaps spatial fishing restrictions that result in lowering the slope of the curve.

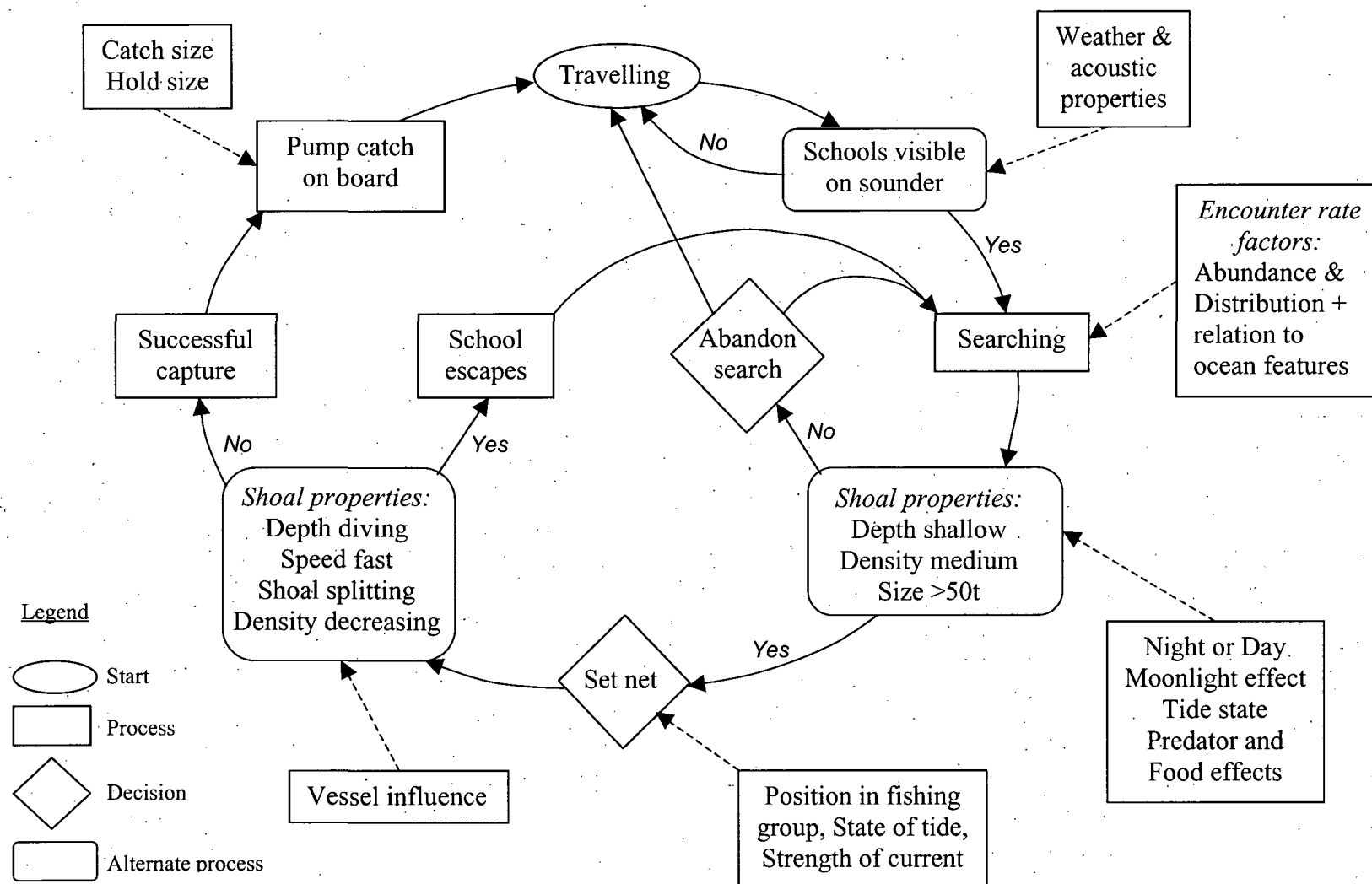


Figure 6.11 Conceptual model of linkages between shoaling and fishing dynamics in a herring seine fishery (adapted and modified from Hart, 1993).

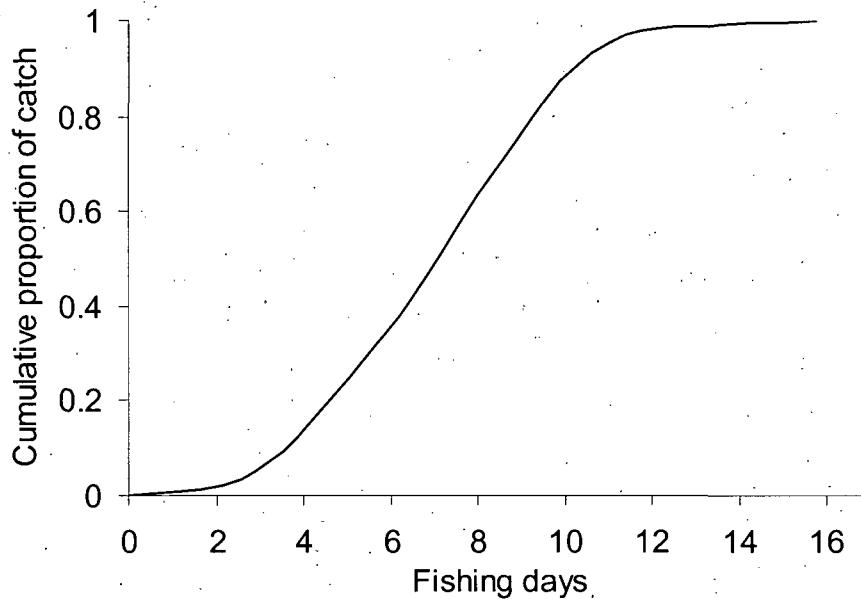


Figure 6.12 Hypothetical performance curve.

It is also possible to compare the projected total annual yield (and its variance) of the modelled fishery with the target quota. Estimation of projected yield, $y(t)$, is accomplished on each time interval by dividing the cumulative catch of time period, $C(t)$, by the expected cumulative proportion of catch, $P(t)$, that may be derived from historical trends or by modelling (see Mundy et al. 1985),

$$y(t) = C(t)/P(t) \quad \dots(6.16)$$

An estimate of the variance of the projected yield is given by Walters and Buckingham (1975);

$$\sigma^2_{y_t} = \frac{C_t^2 \sigma_{P_t}^2}{P_t^4} \{1 + 2(2 \sigma_{P_t}^2 / P_t^2)\} \quad \dots(6.17)$$

DISCUSSION

Although space-time restrictions may promote short-term inefficiency (Sissenwine and Kirkley, 1982) through the creation of uneconomical competition (Walters and Parma, 1996), this may be the very rate limiting process that is required to ensure that exploitation is never too high. An immediate cost is paid for the hope of future benefits. The ability to provide space-time harvest control options in which only a certain proportion of the stock is made vulnerable to capture would reduce such heavy reliance on predicting the abundance of fish stocks prior to harvest. This would be beneficial in three respects; (i) eliminate the inherent biases associated with

assessment techniques that use fishery data in the retrospective determination of stock abundance and assume catch per unit effort to be constant (e.g. Sinclair et al. 1985), (ii) reduce costs, since data requirements are less (Sissenwine and Kirkley, 1982; Hilborn, 1986), and (iii) increase reliability and enforcement (Hilborn, 1986). Other benefits of space-time restrictions include; easily administered and enforced (if not on a fine scale), they are usually supported by the fishing industry itself and, long-term potential benefits accrue (Sissenwine and Kirkley, 1982).

Implementation is very dependent on the nature of the fishery and thus development of tactics requires specific local knowledge (Hilborn and Walters, 1992). Since this knowledge cannot readily be incorporated in to traditional numerical models, a heuristic model may be better suited. Using a fuzzy logic based system it is possible, as I have shown, to build a model that captures knowledge and applies it in quantitative manner. Moreover, since fuzzy logic can model words mathematically it is capable of capturing the uncertainty and vagueness associated with local knowledge. Such an approach is already being explored by Millischer (pers. comm).

Theoretical consideration of benefits of harvest tactics are all very well, but rarely are such options perfectly suited for implementation. In reality, simply achieving optimum control from a biological perspective is insufficient. Decision makers implementing harvest control tactics are faced with making trade-offs between multiple objectives such as conservation, safety and product quality (Fig 6.13). *Public safety* requires considerations of the physical well being of the harvesters. For example, seasonal restrictions may not be a wise choice of control if this requires fishermen to fish in severe weather conditions that could have otherwise been avoided. *Product quality*, particularly in roe-herring fisheries is a function of time and inappropriate scheduling of fishing periods can lead to loss of millions of dollars of product. *Equitable distribution* of catch may also be an appropriate objective. Since objectives of harvest control may be mutually exclusive, priorities must be established before the fishing season starts and even before the regulations are written.

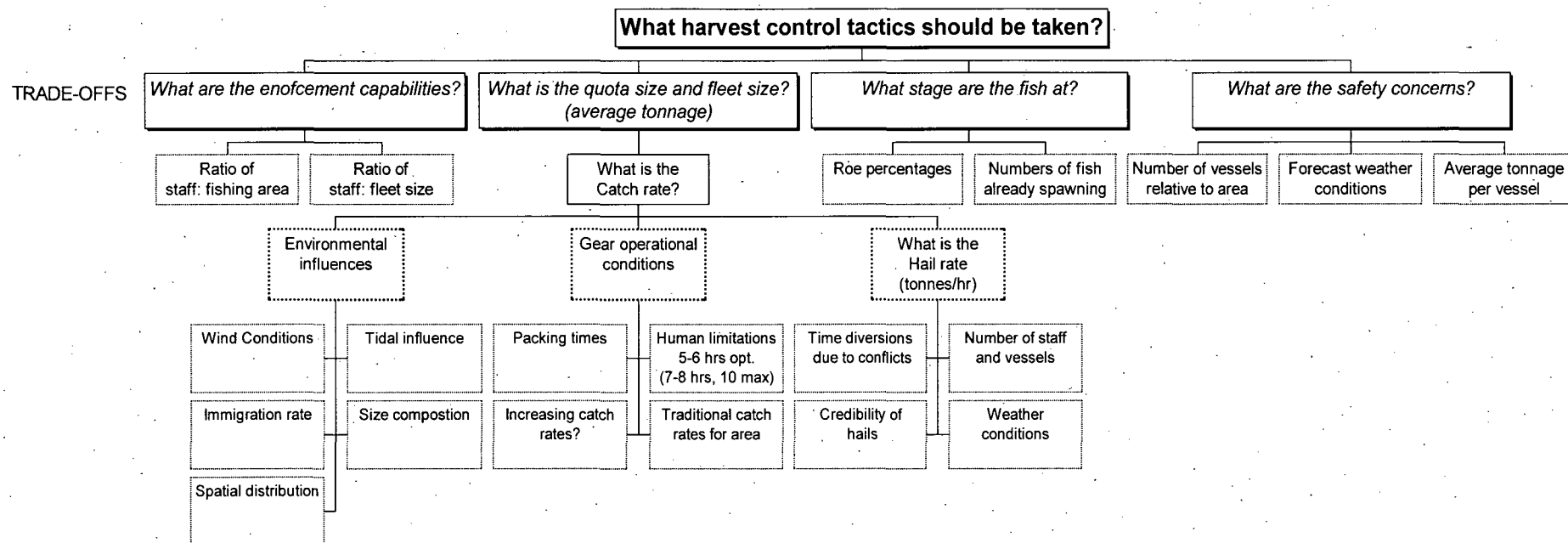


Figure 6.13 Summary of decisions on harvest control tactics in British Columbia roe herring gillnet fishery. Decisions on harvest control are made at two levels. *How much* and *who gets it* is decided during consultative meetings of DFO and industry prior to the fishery. *Where* and *when* to fish is decided in-season and although there is some consultation with industry, responsibility for these decisions rests with specific fishery managers. Based on the information available, the manager has to decide on appropriate tactics in an attempt to meet multiple, often conflicting, objectives. Faced with a series of trade-offs and many uncertainties, decisions are made based on experience and best available knowledge.

Chapter 7

Summary and concluding comments

According to the principle of natural selection, each individual animal is assumed to maximise its inclusive fitness (Milinski and Heller, 1978). Since several conflicting demands may simultaneously influence behaviour, what action an animal takes should depend both on internal factors (e.g. age, longevity, condition) and external factors (e.g. predation risk, food abundance, and season). The interactions of these factors lead to alternative behavioural decisions under different circumstances, in order to maximise fitness (Magnhagen, 1993) (Fig. 7.1).

Herring display a remarkable behavioural plasticity that provides for an adaptive life history trajectory which takes account of changing local environmental conditions and thus allows greater flexibility than one under fixed allelic control (Metcalf, 1993). This life strategy has been termed the 'preferred-conservative life strategy' (Fernö et al. 1998) and has been shaped by an evolutionary arms race (Dawkins and Krebs, 1979) with predators and also by foraging and trade-offs with reproduction (Fig 7.1). The basis of the herring's adaptive flexibility lies in decisions of individual fish, that make second to second evaluations of possible trade-offs, deciding accordingly whether to join, leave or stay with a shoal (Pitcher and Parrish, 1993). On a seasonal basis, these trade-offs change the structure and distribution of shoals in a qualitatively predictable way (Morgan, 1988), yet also help explain huge variability within and between shoals observed in the field (Misund, 1993a).

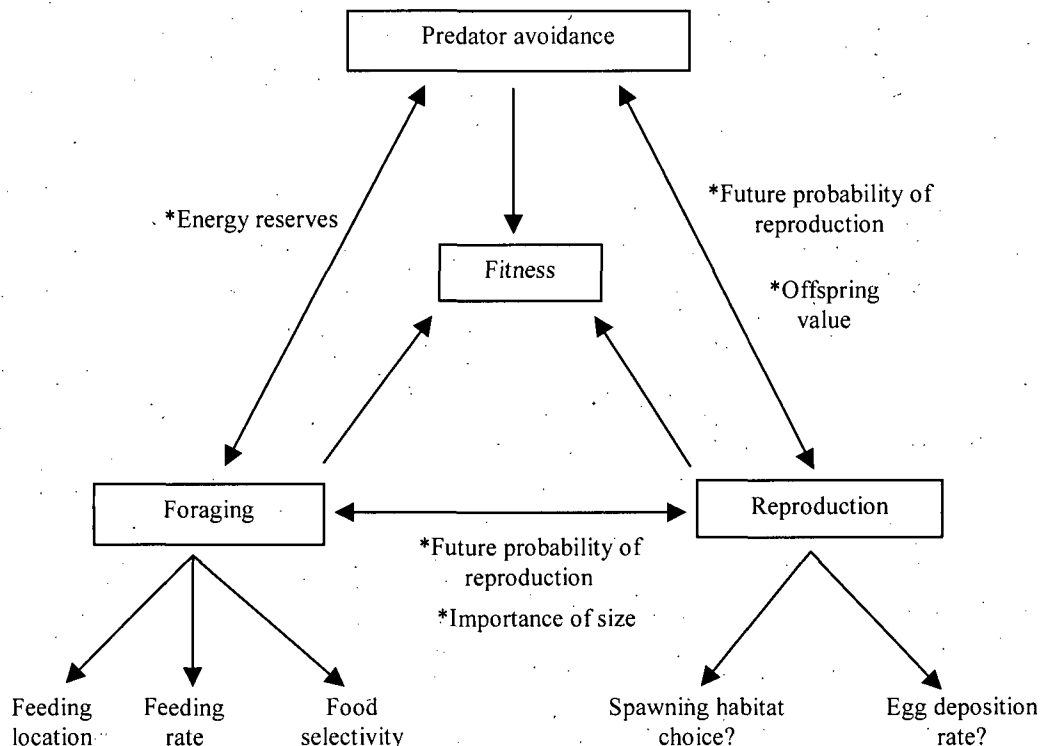


Figure 7.1 A herring's fitness depends on several conflicting demands. E.g. predation risk, can influence fitness both directly and through influencing foraging and reproductive behaviour in different ways. Trade-offs between conflicting demands (\leftrightarrow) are influenced by several factors (examples marked by *). Modified and adapted from Magnhagen (1993).

"It is increasingly important to understand and forecast larger scale phenomena in fish shoaling since it is at this level that shoaling behaviour has the greatest impact on commercial fisheries for shoaling species" (Pitcher and Parrish, 1993)

Observing, characterising and predicting patterns and variation in structure, dynamics and distribution of fish shoals is a worthy objective of considerable importance to fisheries management for 4 reasons:

- (i) Ecological and social mechanisms that underpin shoal structure and distribution may be central to the determination of stock structure:- the number of herring stocks and the geographic location of their respective spawning sites may (or may not, see Smith and Jamieson, 1986) be determined by the location, and extent of geographically stable larval retention areas (Isles and Sinclair, 1982). Even though straying occurs from adult herring homing repeatedly to the same spawning site, the fact that significant differences do persist between population argues strongly for the existence of some sort of mechanism that produces and maintains a complex population structure. An alternative explanation to Isles and Sinclair (1982) larval retention areas is the metapopulation concept (Levins, 1968) put forward by McQuinn (1997). A key part of the concept that differs from Isles and Sinclair, is that strays are not evolutionary losers, rather they are migrants. Homing is thought to develop by spatial learning rather than imprinting. The establishment of a familiar area involves an individual developing spatial memory of its territory which is enlarged through exploratory migrations. Spatial learning is more advantages for fishes that have the opportunity to repeat experiences; those with multiple age classes where recruits might learn by social transmission from seasoned spawners and reinforce the experience throughout their life. Schooling behaviour is likely to play a fundamental role. Corten (1993) suggested that learning of traditional spawning sites and migration patterns explains the present structure of the herring populations in the North Sea.
- (ii) Variation in behavioural dynamics and aggregation pattern of shoaling fish leads to bias in stock assessments (Fréon et al. 1993; Soria et al. 1996; Misund, 1997) for two reasons. First, the increasing catchability phenomena subsumes the classic assumption of a linear relationship of abundance and catch per unit effort embedded in most stock assessment techniques, thus resulting in bias (Sinclair et al. 1985). Second, it is difficult to design sampling procedures independent of fisheries statistics that provide a suitable index of abundance; although, there have been significant developments in the use of acoustic and sonar studies for sampling shoaling pelagic fish.
- (iii) Whilst schooling behaviour can catalyse rapid decline of heavily fished stocks (MacCall, 1976; Ulltang, 1980; Winters and Wheeler, 1985; Csirke, 1989; Pitcher, 1995; Mackinson et al. 1997), it is also suspected be the key to their resilience (Pitcher, 1997):- the technology and techniques employed in modern herring fishing fleets ensures efficient detection and capture of shoals. Combined with this, maintenance of average shoal size and reduction of range during stock decline results in fishers achieving and almost constant catch per unit effort. For depleted stocks, social mechanisms associated

with shoaling behaviour may be central in maintaining integrity of reproductive units and thus enhance rapid rebuilding.

- (iv) In-season harvest control can benefit from knowledge of meso-scale spatial (0.1 to 10's km) and temporal (hours to weeks) changes related to behaviour and distribution that may have dramatic impacts on catch rates (Millischer and Gascuel, 1998):- the importance of harvest strategies has been discussed many authors (e.g. Sissenwine and Kirkley, 1982; Hilborn, 1986; Hall et al. 1988; Hilborn and Walters, 1992; Walters and Parma, 1996). Studies indicate that although a fixed escapement strategy would provide greatest long term yields, fixed harvest policies are more robust for species such as herring that naturally show great variation in abundance. But, even when harvest strategies are clearly defined, failure to successfully implement the strategy can result in a significant increase in the vulnerability to over-exploitation. A clearer understanding of how behaviour determines the distribution and structure of herring shoals may offer us the tools to design robust 'exposure-limitation' in-season harvest strategies, that move away from the necessity to set total allowable catches based on pre-season stock forecasts.

"All internal and external factors interact in a complex way; therefore, modelling fish school structures and behaviours - or, generally speaking, pelagic fish behaviour - represents a challenge, the answer to which unfortunately is at present out of our reach" (Fréon et al. 1992)

In this thesis, the approach taken to understanding and predicting how behaviour determines spatial distribution and shoal structure was to combine and maximise the potential of two fundamental sources of information: (i) 'practical knowledge' from interviews with experts and fishery professionals including; fishers, fishery managers, scientists, First Nations people; (ii) 'hard data' from fieldwork and published sources. Expert system software was used as a tool to structure and compile information from both sources in the form of heuristic rules. To my understanding, this approach is a unique use of an expert system in fisheries management and offers considerable promise as a formal framework for bridging knowledge gaps (Mackinson and Nøttestad, 1998) necessarily required to solve complicated problems that may be lacking in quantitative data yet rich in practical information.

"The best weather for fishin' on the hoom fishin' was after a good sou' west breeze, and then fall away. You know, drop away. Say a good ol' force 6 or 7 and then drop away. Drop away to about 2 or 3, 3 or 4. They used to stick their snouts in then and swim up then, they did. But on the real hoom fishin', on the full moon, that could be calm or anything, yit that allus seemed you got herrin'. On the October full moon, and November - anywhere about that time. Yis, you could git 'em in fine weather, except when that wun't very dark and there was a flat calm. You wun't git much then." 'Jumbo' Fiske (1905-1977)
'probably the greatest herring skipper of the 20th century' Butcher, (1985).

Although the magnitude and relevance of local knowledge in resource management has been recognised for some time (Johannes, 1978; Dahl, 1989; Maquire et al. 1994; RIFM symposium,

1996) a mismatch remains between that which is known and that which is used for any practical sense. Resource management decisions are typically based on detailed, yet limited studies of a more traditional scientific nature, 'hard science'. Despite recognising the obvious need to incorporate local knowledge into science and management, two important barriers still exist; the reluctance to give it respect equal to that given to 'hard science' and the inability to incorporate it in a holistic meaningful way (Mackinson and Nøttestad, 1998). The former is deep rooted and requires a fundamental change in our scientific approach; a point recognised by Chambers (1980), who comments "the most difficult thing for an educated expert to accept is that poor farmers may often understand their situations better than he does. Modern scientific knowledge and the indigenous technical knowledge of rural people are grotesquely unequal in leverage. It is difficult for some professions to accept that they have anything to learn from rural people, or to recognise that there is a parallel system of knowledge to their own which is complementary, that is usually valid and in some aspects superior".

Recently, there have been several attempts at achieving the latter. For example, Neis et al. (1996) conducted a thorough series of interviews with cod fishers in Newfoundland, the results of which convincingly demonstrated that local knowledge, formerly treated as anecdotal and then overlooked, was capable of contributing detailed scientific information on stock structure, changes in catchability, abundance during a closed fishery and potential impacts of a reopened capelin fishery on northern cod recruitment. Specific knowledge of fishers also included awareness of the relationships between season, winds, tides, water temperature, the presence of other species and the ease of capture of fish. Moreover, the relationship between fish size, value and effort means fishers take note of the size distribution of fish (Neis, 1992). Case studies by Pinkerton and Weinstein (1995) highlight how local knowledge can be applied to great benefit under a system of community based management. In a study of the Pacific herring bait fishery, Schweigert and Linekin (1990) also recognise the value of local knowledge. Questionnaires were used to obtain information on spatial distribution of non-migratory herring that are not sampled or assessed as part of the routine monitoring of the major adult migratory populations. The approach taken in this thesis compliments these approaches, but goes one step further by combining both local and scientific knowledge using a formal framework in the form of an expert system.

Analysis of information gleaned from scientific literature and through interviews revealed little difference in the compliment of knowledge. On no occasion did information conflict. However, information from interviews (mostly fishers) was clearly of practical nature, being applied to maximise catches. Knowledge gained through interviews contributed critical information on aspects of herring behaviour and distribution that are not easily experimented upon and have not been reported from scientific field studies.

Until recently, the focus of many scientific studies have been confined to either the fine scale (experimental tank behavioural observations) or large scale (migration and stock distribution,

e.g. Harden-Jones, 1968; McKeown, 1984). As a consequence, many 'holes' in scientific understanding still exist, particularly within the meso-scale realm. Interpretation of behavioural dynamics and distribution of herring requires explicit consideration of spatial and temporal scales since no single mechanism can explain the pattern on all scales. The meso-scale 'wild' studies conducted during this thesis employ high resolution sonar and echo-sounders as observation tools. The 'cluster ratio' (mean nearest neighbour distance: mean of the average inter-shoal distance) is used as a descriptive quantitative index to link scales of distribution pattern within and between herring shoals. Evidence from field studies in Norwegian Sea and Pacific (Chapter 2), suggests that when viewed using an echosounder, the pattern of shoal distribution is similar during different seasons (but not at the same scale). In general, shoals of similar size are found to be tightly aggregated, whilst clusters are patchily distributed. Heightened feeding motivation appears to play the most important role determining shoal size, density and meso-scale spatial distribution of ocean feeding Norwegian spring-spawning herring, whilst changes in maturation state, and behavioural adaptation to local predation risk and seabed substrate/topography are more important for pre-spawning Pacific herring. Very large shoals may be an anti-predator tactic during 'holding' stages of life cycle, whilst smaller shoals may be better suited for 'travelling' stages where rapid co-ordinated manoeuvres may be required. During both ocean feeding and pre-spawning, typical diurnal migrations account for a considerable amount of temporal variability in structure and vertical distribution that potentially mask spatial variation if not explicitly considered.

Despite recent attempts to link cross scale behaviour dynamics and distribution studies, much of our understanding of fish distribution and behaviour remains qualitative or highly uncertain. Such information does not lend itself well to mathematical representation and consequently, traditional numerical modelling used for decision making may be unsuitable. The 'knowledge-based system' (Expert System) used here offers an alternative way of representing and applying our knowledge to solve fisheries problems in general. Some of the useful qualities that expert systems applications provide include;

- pulling together and storing knowledge of experts making it easily available
- knowledge can be readily added to or modified at a later stage
- clarifying knowledge and problem solving approaches, leading to better decisions
- thorough and systematic, nothing is forgotten
- ability to represent both heuristic and algorithmic numerical information
- allowing for reasoning under uncertainty
- integrating knowledge from different sources and of quality

Use of expert systems is an admission that our knowledge is incomplete or uncertain. Through building and testing we move toward practicality, recognising that decisions based on qualitative and sometimes incomplete knowledge is still better than making decisions without any understanding (Saila, 1996).

"When the only tool you have is a hammer, all your problems look like nails"
Lotfi Zadeh

Application of fuzzy logic provides the ability to map linguistic expressions on to numerical variables, or 'practical knowledge' on to 'hard data'. Humans perceive the precise in a fuzzy way and it is this ability to summarise information in to classes (fuzzy sets) that separates human intelligence from machine intelligence (Zadeh, 1973). Definition of fuzzy sets allows CLUPEX to capture the vagueness and uncertainty associated with language that is not possible with conventional mathematical tools whose crisp definitions force break points. Similarly, natural systems do not conform to crisp definitions. By allowing us to assign degrees of confidence simultaneously to various possible options (defining membership functions of a fuzzy set), fuzzy logic provides an organised method for dealing with imprecision of data. It makes it possible to take in to account the grey areas of data, thus providing the ability to more closely reflect the real world.

Provided with input on biotic and abiotic conditions CLUPEX operates using heuristic rules to provide quantitative and qualitative predictions on the structure, dynamics and meso-scale distribution of adult herring shoals during different life stages. Reflecting the variability observed in nature, a range of values is predicted for each quantitative descriptor and, for qualitative descriptors, several choices may occur simultaneously for any descriptor; each choice has an associated confidence value that defines the relative importance between choices. GEOSPACE group (1993) provide support for prediction of ranges for each descriptor: "...it is impossible to consider spatial structures of shoals as being exclusively produced by environmental constraints. According to the ethology of the populations, several spatial structures may be the answer to a single hydrological or tropic organisation".

Test predictions of the model corresponded well with observed patterns, although accuracy for specific circumstances was limited by the resolution of the knowledge. However, by adding specific local knowledge and adjusting weighting parameters, the model can be adapted to provide more accurate and precise predictions. The user interface combines hypertext and an explanation facility that is fully cross-referenced to a database, to provide an intuitive and transparent feel rarely found in more traditional analytical models.

Visualisation of structure and meso-scale distribution of herring shoals was performed using a simulation model, ShoalPattern. The model uses random sampling of gamma distributions for quantitative output parameters from CLUPEX to display changes in shoal size, packing density and shoal cluster patterns. Visualisation clearly characterises seasonal changes in shoal distribution patterns. The re-sampling scheme and setting of limits to sampling of gamma distributions, provide the ability to generate many potential shoal patterns that satisfy the initial conditions input to CLUPEX, thus reiterating the point noted above "...several spatial structures may be the answer to a single hydrological or tropic organisation". By specification of the

gamma distribution parameters the model has close links to empirical data and thus its predictions could be improved if seasonal and regional data were available to parameterise the model. Inclusion of habitat features and preferability restrains and considerably alters the initial distribution patterns.

One of the obvious benefits of an approach utilising non-scientists knowledge combined with more typical scientific data is greater acceptability of fisheries science and the recommendations that it offers. Stake-holders who may directly be influenced by management actions may contribute information central to the formulation of scientific recommendations to management. Intuitively, this involvement provides a sense of worth and pride and thus may be instrumental in fostering greater responsibility of fishers to the resource. More time spent communicating would reduce the present knowledge gap, enhance mutual respect and foster co-operative responsibility, and thus likely avoid some errors in management that have resulted in conflict in the past. Going one step further, the mutual respect that could develop through continued dialogue and information sharing may pave the way to localised co-management of fish stocks. Such a management system may be vital to rebuild the spatial diversity that many fish stocks once exhibited (and which may be crucial to their resilience). One example in which fishermen have taken greater responsibility is through a legislated system of co-management with government regulators in the Lofoten cod fishery of northern Norway (Jentoft and Kristoffersen, 1989). A further example is the management of local-spawning sub-sets of Strait of Georgia herring in British Columbia. Kew and Griggs (1991) noted that commitment to a specific place and local control meant that kinship groups developed a sense of belonging which reinforced feelings of dependence on, and respect for local resources (from Gillis and Ellis, 1995). Current management of the Northwest Atlantic 4WX herring fishery off Nova Scotia has developed through a system of consultative arrangements and co-management. Through the Monitoring Working Group, an in-season management scheme has been implemented that makes decisions regarding the appropriate distribution and rate of fishing during the season based on the best available information. Specific effort has been directed to improving the observation integrity and intensity by incorporating fishers local knowledge (Stephenson 1997, and pers.comm). Further examples can be found in Pinkerton and Weinstein (1995) who provide detailed success stories of community based co-management regimes.

Use of heuristic rules combined with theory of fuzzy sets provides intuitive and practical methods that are being widely adopted across many disciplines. In the field of process control, engineers have clearly demonstrated that a system of rules is easier to derive and faster to use. Looking toward future applications in natural resource management and fisheries in particular, several areas of possible application are briefly identified:

- (i) Descriptive and predictive modelling: models of natural processes could benefit tremendously from use of fuzzy concepts. The use of fuzzy algorithms allows development of systems not bound by linearity, continuity or stationarity. Despite incomplete, uncertain and qualitative information, the system can be defined in terms of

rules describing processes. In so doing, we also identify areas in which knowledge (rules) are lacking, thus focussing on potential research areas. Such models can be used to demonstrate how the behaviour of complex systems changes. Specifically, there is considerable potential for applying principles of fuzzy logic to modelling shoaling fish dynamics.

- (ii) Risk assessment and Decision analysis: An important aspect of decision making involves the explicit consideration of uncertainties and risks when evaluating possible management actions. Decisions in environmental issues are usually complex involving many components and variables with little quantifiable processes. Fuzzy heuristic systems provide an alternative approach to the description of uncertainties in situations too complex or too ill-defined to allow precise mathematical analysis, offering a simple framework to gather information and to combine expert and lay-expert knowledge by means of linguistic variables and rules. Alternatively, it is possible to use the heuristic approach to better define the limits and distribution of the prior probabilities for Bayesian decision analysis.
- (iii) Pattern recognition in data structures: the method of iterative clustering in model-free estimation of stock-recruitment relationships (Mackinson et al. 1999a) provides a good example. We identify and generate patches using a fuzzy cluster algorithm and then associate stock and recruitment by defining rules in a fuzzy system. Looking for pattern in spatial data is another obvious source of this type of application. For large data structures, neural networks can be used to search for patterns.
- (iv) Acoustic data filtering for identification of fish species and schools. Using fuzzy sets simple rules could be implemented to describe conditions for selecting schools of fish from acoustic outputs. Selection criteria may include rules on echo intensity and number of continuous pings within a signal.

CONCLUSION

Seasonal changes in internal motivational state combined with individual behavioural adaptation to spatial and temporal changes in the local biotic and abiotic environment are manifest as qualitatively predictable changes the structure, dynamics and distribution of herring shoals. Applying heuristics and fuzzy logic to form a coalition between qualitative and quantitative sources of knowledge on herring behaviour and shoal distribution, CLUPEX uses input on biotic and abiotic environmental conditions to predict structure, dynamics and meso-scale distribution of shoals of migratory adult herring during different stages of their annual life cycle. An important feature of the model is that predictions constitute testable hypotheses on which to base future experiments and field observations. In my work so far, test predictions correspond well with observed shoal patterns, although accuracy for specific circumstances may be limited by the resolution of the knowledge. However, by adding specific local knowledge and adjusting weighting parameters, CLUPEX can be adapted to provide more accurate and precise predictions. The user interface combines hypertext and an explanation facility that is fully cross-referenced to a database, to provide an intuitive and transparent feel rarely found in more traditional analytical models. Model predictions are fundamental in the design and implementation of space-time harvest strategies for shoaling pelagic species.

References

- Abrahams, M.V. and Colgan, P.W. 1985. Risk of predation, hydrodynamic efficiency and their influence on school structure. *Environmental Biology of Fishes* 13, 195-202.
- Anderson, J.J. 1981. A stochastic model for the size of fish schools. *Fishery Bulletin* 79(2): 315-323.
- Andorfer, K. 1980. The shoal behaviour of *Leucaspius delineatus* (Heckel.) in relation to ambient space and the presence of a pike, *Esox lucius*. *Oecologia*, 47: 137-140.
- Aneer, G, G. Florell, U. Kautsky, S. Nellbring and L. 1983. In-situ observations of Baltic herring (*Clupea harengus membras*) spawning behaviour in the Asko-Landsort area, northern Baltic proper. *Mar. Biol.* 74: 105-110.
- Anker-Nilssen, T. and Barrett, R.T. 1991. Status of seabirds in northern Norway. *Brit. Birds* 84:329-341.
- Anonymous, 1988. Report of the herring assessment working group for the area south 62°N. *Int. Council. Explor. Sea C.M.* 1988/Assess: 17: 205p.
- Anthony, V.C. and M.J. Fogarty. 1985. Environmental effects on recruitment, growth and vulnerability of Atlantic herring in the Gulf of Maine region. *Can. J. Fish. Aquat. Sci.* 42 (Suppl 1): 158-173.
- Anthony, V.C. and Waring, G. 1980. The assessment and management of the Georges Bank herring fishery. *Rapp P.-v. Réun. Cons. Int. Explor. Mer.* 177: 72-111.
- Aoki, I., Inagaki, T., Mitani, I., Ishii, T. 1989. A prototype expert system for predicting fishing conditions of anchovy of the coast of Kanagawa Prefecture. *Bull. Jap. Soc. Fish. Ocean.* 55 (10): 1777-1783.
- Aoki, I., and Komatsu, T. 1997. Analysis and prediction of the fluctuation of sardine abundance using a neural network. *Oceanol. Acta* 1997, 20 (1): 81-88
- Armstrong, R.W. 1986. The 1986 roe herring charter vessel monitoring and sampling program. *Can. Ind. Rep. Fish. Aquat. Sci.* 172: 110 p.
- Axelsen, B.E. 1997. Stimodynamikk hos sild (*Clupea harengus* L.) under gyting. Master thesis, University of Bergen. 95p.
- Axelsen, B., L. Nøttestad, A. Ferno, A. Johannesson and O.A. Misund. 1998. Await in the pelagic: herring compromising reproduction and survival within a vertically split school. *ICES CM* 1998/J:19. 20 pages.
- Bailey, K.M. 1989. Interaction between the vertical distribution of juvenile walleye pollock *Theragra chalcogramma* in the eastern Bering Sea, and cannibalism. *Marine Ecology Progress Series.* 53: 205-213.
- Baker, R.R. 1978. The evolutionary ecology of animal migration. Hodder and Stoughton, London.
- Baumgartner, T., Soutar, A., and Ferreira-Bartrina, V. 1992. Reconstruction of the history of Pacific sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara basin, California *CalCoFI Rep.*, Vol. 33: 24-40.
- Beddington, J.R. and R.M. May. 1977. Harvesting natural populations in a randomly fluctuating environment. *Science* 197:463-465.
- Bezdek, J.C., Hathaway, R., Sabin, M., Tucker, W.T. 1987. Convergence theory for fuzzy c-means: counterexamples and repairs. *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-17, no. 5. 873-877. Reprinted in Bezdek, J.C. (ed.) *Fuzzy models for pattern recognition: methods that search for structures in data.* New York: Institute of Electrical and Electronics Engineers, c1992. 539p.
- Begon, M., Harper, J.L., and C.R. Townsend. 1990. *Ecology: individuals, populations and communities.* 2nd edn. Blackwell Scientific Publications, Oxford. Book. 945p.
- Bergstad, O.A., Røttingen, I., Tøresen, R., Johannessen, A., & Dragesund, O. 1991. Return of Norwegian spring spawning herring (*Clupea harengus* L.) to historical spawning grounds of south-western Norway. *ICES C.M.* 1991/H:24:1-14. Pelagic fish committee.
- Beverton, R.J.H. 1990. Small marine pelagic fish and the threat of fishing; are they endangered? *J. Fish. Biol.* 37 (Suppl A): 5-16.
- Beverton, R.J.H., Cooke, J.G., Csirke, J.B., Doyle, R.W., Hempel, G., Holt, S.J., MacCall, A.D., Policansky, D.J., et al. 1984. Dynamics of a single species. Exploitation of marine communities. Report of the Dalhem workshop on exploitation of marine communities, Berlin April 1-6, 1984. May, R.M. [ed.] *Life Sci. Res. Rep.* 32: 13-58.
- Bishop, C. 1995. *Neural Networks for Pattern Recognition.* Oxford: University Press.

- Blaxter, J. H. S. and Holliday, F. H. 1969. The behaviour and physiology of herring and other clupeids. *Advances in Marine Biology*, 1: 261-393.
- Blaxter, J.H.S. 1985. The herring: a successful species? *Can. J. Fish. Aquat. Sci.* 42 (Suppl. 1): 21-30.
- Blaxter, J.H.S. and J.R. Hunter. 1982. The biology of clupeoid fishes. *Adv. Mar. Biol.* 20: 1-223.
- Blindheim, J. 1989. Ecological features of the Norwegian Sea. Pp. 366-401 in: Rey, L. and V. Alexander [eds.]. *Proceedings of the sixth conference of the Comité Arctique International 13-15th may 1985*. E.J. Brill, Leiden.
- Bolster, G.C. 1958. On the shape of herring schools. *J. Cons. Int. Explor. Mer.* 23, 228-34.
- Borstad, G.A., D.A. Hill, R.C. Kerr and B.C. Nakashima. 1992. Direct digital remote sensing of herring schools. *Int. J. Remote Sens.* Vol 13(12):2191-2198.
- Breder, C.M. 1951. Studies on the structure of fish shoals. *Bull. Am. Mus. Nat. Hist.*, 98: 1-27.
- Breder, C.M. 1959. Studies on social grouping in fishes. *Bulletin of the American Museum of natural History* 117: 393-482.
- Breder, C.M. 1967. On the survival value of fish schools. *Zoologica* 52, 25-40.
- Breder, C.M. 1976. Fish schools as operational structures. *Fish. Bull. U.S.* 74, 471-502.
- Brock V.E. and R.H. Riffenburgh. 1960. Fish schooling: a possible factor in reducing predation. *J. Cons. Perm. Int. Exp. Mer.* 25: 307-317.
- Brodeur, R.D. and M.T. Wilson. 1996. Mesoscale acoustic patterns of juvenile walleye pollock (*Theragra chalcogramma*) in the western Gulf of Alaska. *Can. J. Fish. Aquat. Sci.* 53:1951-1963.
- Buerkle, U. 1985. Acoustic estimation of fish abundance in a large aggregation of herring. *Can. Atl. Fish. Sci. Advis. Comm. Res. Doc* 85/62.
- Buerkle, U. 1983. First look at herring schools with a bottom referencing underwater towed instrumentation vehicle, "BRUTIV". *FAO Fish. Rep. No.* 300: 125-130.
- Buerkle, U. 1987. Results of the 1986 and 1987 winter acoustic surveys of NAFO Div 4WX herring stocks. *Can. Atl. Fish. Sci. Advis. Comm. Res. Doc* 87/36.
- Buerkle, U. 1989. Results of the 1989 winter acoustic survey of NAFO Div 4WX herring stocks. *Can. Atl. Fish. Sci. Advis. Comm. Res. Doc.* 89/41.
- Buerkle, U. 1990. Results of the 1990 winter acoustic survey of NAFO Div 4WX herring stocks. *Can. Atl. Fish. Sci. Advis. Comm. Res. Doc.* ??
- Buerkle, U., and R.L. Stephenson. 1990. Herring school dynamics and its impact on acoustic abundance estimates. *Proc. Int. Herring. Symposium.* Oct. 1990. Anchorage, Alaska Sea Grant. Pp185-207.
- Burd, A.C. 1990. The North Sea herring fishery" an abrogation of management. *Proc. Int. Herring. Symposium.* Oct. 1990. Anchorage, Alaska Sea Grant. Pp 1-22.
- Burton, S.F. 1990. Comparison of Pacific spawner herring biomass estimates from hydroacoustic trawl and spawning ground escapement surveys in Puget sound, Washington. *Proceedings of the International Herring Symposium, October 1990. Anchorage, Alaska.* 209-221.
- Butcher, D. 1985. *The Driftersmen*. Tops'1 books. 152p.
- Castillo, J., Baarbieri, M.A., Gonzalez, A. 1996. Relationships between sea surface temperature, salinity, and pelagic fish distribution off northern Chile. *ICES J. Mar. Sci* 53: 139-146.
- Chambers, R. 1980. The small farmer is a professional. *Ceres*, March-April:19-23.
- Christensen, I., Haug, T., & Øien, N. 1992. Seasonal distribution, exploitation and present abundance of stocks of large baleen whales (Mysticeti) and sperm whales (*Physeter macrocephalus*) in Norwegian and adjacent waters. *ICES Journal of Marine Science*, 49:341-355.
- Clark, C.W. 1974. Possible effects of schooling on the dynamics of exploited populations. *J. Cons. Int. Explor. Mer.* 36 (1): 7-14.
- Clark, C.W., and M. Mangel. 1979. Aggregation and fishery dynamics: a theoretical study of schooling and the tuna purse seine fisheries. *Fish. Bull. U.S.* 77(2):317-337.
- Clark, F.N. 1956. Average lunar month catch of sardine fishermen in southern California 1932-33 through 1954-55. *Calif. Fish. Game.* 42: 309-323.
- Colgan, P. 1993. The motivational basis of fish behaviour. In: Pitcher, T.J. (Editor), *The Behaviour of Teleost Fishes*, 2nd ed. Chapman and Hall, London & Sidney. pp31-50.
- Conan, G.Y., U. Buerkle, E. Wade, M. Chadwick, and M. Comeau. 1988. Geostatistical analysis of spatial distribution in a school of herring. Copenhagen- Denmark - ICES 1988. 14 pp. (ICES-CM-1988/D:21)

- Corten, A. 1993. Learning processes in herring migrations. ICES C.M.1993/H:18 Pelagic Fish Committee.
- Crawford, R.H. 1980. A biological analysis of the herring from the Atlantic coast of Nova Scotia and Eastern Northumberland Strait. - Manuscript Technical report series Nova Scotia. Department of Fisheries Halifax 80-03.
- Csirke, J. 1988. Small shoaling pelagic fish stocks. p271-302. In J.A. Gulland [ed.] Fish population dynamics. (2nd edition) John Wiley and Sons. New York.
- Csirke, J. 1989. Changes in the catchability coefficient in the Peruvian anchoveta (*Engraulis ringens*) fishery. p 207-219. In: D. Pauly, P. Muck, J. Mendo and I. Tsukayama (Editors). The Peruvian upwelling ecosystem: dynamics and interactions. ICLARM. Conference proceedings 18, 438 p. ICLARM, Manila, Philippines.
- Cushing, D.H. 1980. The decline of the herring stocks and the gadoid outburst. J. Cons. Int. Explor. Mer. 39: 70-81.
- Daan, N. 1980. A review of replacement and depleted stocks by other species and the mechanisms underlying such replacement. Rapp. P.-v. Réun. Cons. Int. Explor. Mer, 177: 405-421.
- Dabrowski, C.E. and Fong, E.N. 1991. Guide to expert system building tools for computers. National Institute of Standards and Technology, Gaithersburg, MD 20899. Special Publication 500-188, 141 p.
- Dahl, A.L. 1989. Traditional environmental knowledge and resource management in New Caledonia. In Johannes, R.E. [ed.] 1989. Traditional ecological knowledge: a collection of essays. Gland, Switzerland, IUCN, World Conservation Union, pp. 57-66.
- Dawkins, R., Krebs, J.R. 1979. Arms race within and between species. Proc. R. Soc., Lond. 205: 489-511.
- DeAngelis, D.L. 1975. Stability and connectance in food web models. Ecology 56: 238-243.
- Denman, K.L. and Powell, T.M. 1984. Effects of physical processes on planktonic ecosystems in the coastal ocean. Oceanography and Marine Biology annual review. 22:125-168.
- Department of Fisheries and Oceans. 1991. Herring sonar/ sounder technical manual. Internal publication. Pacific Biological Station, Nanaimo, B.C. Canada.
- Dragesund, O., J. Hamre and Ø. Ulltang. 1980. Biology and population dynamics of the Norwegian spring-spawning herring. Rapp P.-v. Réun. Cons. Int. Explor. Mer. 177: 43-71.
- Dragesund, O., Johannessen, A. and Ulltang, Ø. 1997. Variation in migration and abundance of the Norwegian spring spawning herring (*Clupea harengus* L.). Sarsia 82:97-105.
- Dunn, J.C. 1974. A fuzzy relative of ISODATA process and its use in detecting, compact separated clusters. J. Cybern., Vol 3., 32-57. Reprinted in Bedzek, J.C. (ed.) Fuzzy models for pattern recognition: methods that search for structures in data. New York: Institute of Electrical and Electronics Engineers, c1992. 539p.
- Elton, C.S. 1958. The ecology of invasion by animals and plants. Methuen, London.
- Exsys Incorporated, 1997. Exsys professional user manual. 512p. Now owned by Multilogic, www.mulilogic.com.
- Fernö, A., Pitcher, T.J., Nøttestad, L. Melle, W., Mackinson, S., Hollingworth, C., and Misund, O.A. 1998. The challenge of the herring in the Norwegian Sea: making optimal collective spatial decisions. Sarsia 83:149-167.
- Floen, S., B. Totalnd, J.T. Overdall, and O.A. Misund. 1991. A PC-based echo-integrator system applicable for school structure analysis. International council for the exploration of the sea, Copenhagen (Denmark). Council meeting. La Rochelle (France). 26 Sep- 4 Oct. 1991. ICES-CM1991/B:43
- Foster, W.A. and Treherne, J.E. 1981. Evidence for the dilution effect in the selfish herd from fish predation on a marine insect. Nature 293: 466-467.
- Fréon, P., F. Gerlotto and M. Soria. 1992. Changes in school structure according to external stimuli: description and influence on acoustic surveys. Fisheries Research, 15: 45-66.
- Fréon, P., Gerlotto, F., Misund, O.A. 1993. Consequences of fish behaviour for stock assessment. ICES mar. Sci. Symp., 196: 190-195.
- Fréon, P., Gerlotto, F., Soria, M. 1996. Diel variability of school structure with special reference to transition periods. ICES J. Mar. Sci. 53: 459-464.
- Fuchs, F. 1991. An expert system for analysing relationships between fish and the environment, ICES C.M. 1991/D:5, 6pp.

- Fuiman, L.A. and Magurran, A.E. 1994. Development of predator defences in fishes. *Rev. Fish. Biol. Fish.* 4 (2): 145-183.
- Galaktionov, G. 1984. Features of the schooling behaviour of the *Alfonsina Beryx splendens* (Berycidae) in the thalassobathal depths of the Atlantic ocean. *Journal of Ichthyology* 24:148-151.
- GEOSPACE group. 1993. The spatial organisation of aquatic populations as observed using hydroacoustic methods. *Aquat. Living Resour.* 6: 171-174.
- Gerlotto, F., Fréon, P., Soria, M., Cottais, P-H., and Ronzier, L. 1994. Exhaustive observation of 3D school structure using multibeam side scan sonar: potential use for school classification, biomass estimation and behaviour studies. *ICES CM* 1994B: 26, 12 pp.
- Gerlotto, F. & Petitgas, P. 1991. Some elements on time variability in acoustic surveys through the example of a single transect repeated during 24 hours. *ICES C.M.* 1991/B:15. 9 pages.
- Gerlotto, F. and P. Fréon. 1988. Influence of the structure and behaviour of fish schools on acoustic assessment. *ICES C.M.* 1988/B:53
- Gerlotto, F. and P. Fréon. 1992. Some elements on vertical avoidance of fish schools to a vessel during acoustic surveys. *Fish. Res.* 14: 251-259.
- Gibson, R.N. and Ezzi, I.A. 1992. The relative profitability of particulate - and filter feeding in the herring (*Clupea harengus* L.). *Journal of Fish Biology*, 40:577-590.
- Gillis, D and D. Ellis. 1995. The Georgia Strait herring "stock" problem, inclusive of the first nations TEK (Traditional Ecological Knowledge) perspective. In Hay, D.E. and McCarter, P.B. *Proceedings of the 7th Pacific Coast Herring Workshop, January 27-28, 1994. Can. Tech. Rep. Fish. Aquat. Sci.* No. 2060, pp. 171-178.
- Godin, J-G-J. 1986. Anti-predator function of shoaling in teleost fishes: a selective review. *Le Naturaliste Canadien* 113:241-251.
- Godin, J-G.J. 1990. Diet Selection under risk of predation. pps 739-769. In: R.N. Hughes (Editor), *Behavioural Mechanisms of food selection. NATO ASI 20, Springer Verlag, Berlin*, 889pp.
- Godin, J-G.J. and Keenleyside, M.H.A. 1984. Foraging on patchily distributed prey by a cichlid fish: a test of the ideal free distribution theory. *Animal Behaviour* 32:120-131.
- Godin, J-G.J. and Morgan, M.J. 1985. Predator avoidance and school size in a cyprinodontid fish, the banded killifish (*Fundulus diaphanus*). *Behav. Ecol. Sociobiol.* 16: 105-110.
- Godin, J-G.J., Classon, L.J. and Abrahams, M.V. 1988. Group vigilance and shoal size in a small characin fish. *Behaviour* 104: 29-40.
- Gonzalez, L., Gerlotto, F., Cardenas, J.J. 1998. Pelagic fish populations in eastern Venezuela: impact of environmental characteristics on the morphology, aggregation and spatio-temporal distribution of *Sardinella aurita*. *ICES CM/J:13*, 20pp.
- Gordon, L. (Pers. comm). Department of Fisheries and Oceans, Port Alberni, B.C. Canada.
- Grosse, D.J. and D.E. Hay. 1988. Pacific herring, *Clupea harengus pallasi*, in the Northeast Pacific and Bering Sea, p. 34-54. In N.J. Wilimovsky, L.S. Incze, and S.J. Westheim [eds.] *Species synopsis life histories of selected fish and shellfish of the Northeast Pacific and Bering Sea. Washington Sea Grant Publication, University of Washington, Seattle, WA.* 88-2.
- Haegeler, C.W. and Schweigert, J.F. 1985. Distribution and characteristics of herring spawning grounds and description of spawning behaviour. *Can. J. Fish. Aquat. Sci.* 42 (Suppl. 1): 39-55.
- Hafsteinsson, M.T. and Misund, O.A. 1995. Recording the migration behaviour of fish schools by multi-beam sonar during conventional acoustic surveys. *ICES J. Mar. Sci.*, 52:915-924.
- Hager, M.C. and Helfman, G.S. 1991. Safety in numbers: shoal size by minnows under predatory attack. *Behav. Ecol. Sociobiol.* 29: 271-276.
- Haining, R. 1993. *Spatial data analysis in the social and environmental sciences.* Cambridge University Press. 409p.
- Hall, D.L., R. Hilborn, M. Stocker and C.J. Walters. 1988. Alternative harvest strategies for Pacific herring (*Clupea harengus pallasi*). *Can. J. Fish. Aquat. Sci.* 45: 888-897.
- Hamilton, W.D. 1971. Geometry for the selfish herd. *J. Theor. Biol.* 31:295-311.
- Hara, I. 1985. Shape and size of Japanese sardine schools in the waters of southeastern Hokkaido on the basis of acoustic and aerial surveys. *Bulletin of the Japanese Society of Scientific Fisheries*, Nissuishi 52, 41-46.
- Harden-Jones, F.R. 1968. *Fish Migration.* Edvard Arnold (Publishers) Ltd. London. 325pp.

- Hart, A. 1989. Knowledge acquisition for expert systems. New Technology Modular Series, Kogan Page, London.
- Hart, J.L. 1973. Pacific fishes of Canada. Fish. Res. Board Can. Bull. 180: 740 p.
- Hart, P.J.B. 1993. Catching Horse mackerel off Chile: the influence of school behaviour and other fishermen. In, Decision Making by Commercial Fishermen, Fisheries Centre Research Reports Vol 1 (2):15-16.
- Haug, T., Lindstrøm, U., Nilssen, K.T., Røttingen, I., and Skaug, H. J. 1995. Diet and food availability for Northeast Atlantic minke whales *Balaenoptera acutorostrata*. ICES C.M./N:19. Marine Mammals Committee. 33 pp.
- Hay, D.E and A.R. Kronlund. 1987. Factors affecting the distribution, abundance, and measurements of Pacific herring (*Clupea harengus pallasii*) spawn. Can. J. Fish. Aquat. Sci. 44:1181-1194.
- Hay, D.E. and P.B. McCarter. 1998. Herring spawn CD-ROM. Pacific Biological Station, Nanaimo, BC, Canada.
- Hay, D.E. 1985. Reproductive biology of Pacific herring (*Clupea harengus pallasii*). Can. J. Fish. Aquat. Sci 42 (Suppl. 1): 111-126.
- He, P., and C.S. Wardle. 1988. Endurance at intermediate swimming speeds of Atlantic mackerel (*Scombrus scombrus* L.) herring (*Clupea harengus* L.) and saithe (*Pollachius virens* L.). J. Fish. Biol. 33: 255-266.
- Helfman, G.S. 1984. School fidelity in fishes: the yellow perch pattern. Anim. Behav. 32: 663-672.
- Helfman, G.S. and Schultz, E.T. 1984. Social transmission of behavioural traditions in a coral reef fish. Anim. Behav. 32: 379-384.
- Herskin, J and J.F. Steffensen. 1998. Energy saving in sea bass swimming in a school: measurements of tail beat frequency and oxygen consumption at different swimming speeds. J. Fish. Biol. 53: 366-376.
- Hewitt, R.P., Smith, P.E., & Brown, J.C. 1976. Developments and use of sonar mapping for pelagic stock assessments in the California current. Fisheries Bulletin, US, 74, 281-300.
- Hilborn, R. 1986. A comparison of alternative harvest tactics for invertebrate fisheries. Pp. 313-317, In G.S. Jamieson and N. Bourne [eds.] North Pacific workshop on stock assessment and management of invertebrates. Canadian special publication in fisheries and aquatic sciences. No. 92.
- Hilborn, R. and C.J. Walters. 1992. Quantitative fish stock assessment: choice, dynamics and uncertainty. Chapman and Hall Pub. Co., New York.
- Hilborn, R. and Mangel, M. 1997. The ecological detective: confronting models with data. Princeton University Press, Princeton, New Jersey. 315pp.
- Hobson, E.S. 1968. Predatory behaviour of some shore fishes in the Gulf of California. Res. Rep. U.S. Fish. Wildl. Serv. 73, 1-92.
- Holling, C.S. 1959. Some characteristics of simple types of predation and parasitism. Can. Entomol. 91:385-398.
- Hourston, A.S. 1980. The decline and recovery of Canada's Pacific herring stocks. Rapp. P.-v. Réun. Cons. Int. Explor. Mer. 177:143-153.
- Hourston, A.S. 1982. Homing by Canada's west coast herring to management units and divisions as indicated by tag recoveries. Can. J. Fish. Aquat. Sci. 39: 1414-1422.
- Hourston, A.S. and C.W. Haegle. 1980. Herring on Canada's Pacific coast. Can. Spec. Publ. Fish. Aquat. Sci. 48: 23 p.
- Huntingford, F.A. and Wright, P.J. 1993. The development of adaptive variation in predator avoidance in freshwater fishes. Pp45-61. In Behavioural ecology of fishes (Huntingford, F.A., & Toricelli, P., eds.) Proceedings of a conference held at the Ettone Majorana Centre for scientific culture, Erice, Italy, 30 September-5 October 1991. Harwood Academic Publishers, Switzerland.
- Huntingford, F.A., Wright, P.J., and Tierney, J.F. 1994. Adaptive variation in antipredator behaviour in threespine stickleback. In Bell, M.A. and Foster, S.A. [eds.]. The Evolutionary Biology of the Threespine Stickleback. Oxford: Oxford Univ. Press, pp277-296.
- Huse, G. and Giske, J. 1998. Individual based models with evolved fish behaviour. ICES CM 1998/J:16
- Huse, I. and Ona, E. 1996. Tilt angle distribution and swimming speed of overwintering Norwegian Spring spawning Herring. ICES J. Mar. Sci. 53:863-873.
- Hutchings, J.A. 1996. Spatial and temporal variation in the density of northern cod and a review of the hypotheses for the stock's collapse. Can. J. Fish. Aquat. Sci. 53:943-962

- Iles, T.D. and Sinclair, M. 1982. Atlantic herring: stock discreteness and abundance. *Science* 215: 627-633.
- Itazawa, Y., Matsumoto, T. and Kanda, T. 1978. Group effects on physiological and ecological phenomena in fish I – Group effect on the oxygen consumption of the rainbow trout and the medaka. *Bull. Jap. Soc. Scient. Fish.*, 44: 965-969.
- Institute of Marine Research. 1997. Cruise report No. 1997005, R/V <<G.O. Sars>>. Institute of Marine Research, Bergen, Norway. 105pp.
- Jakobsson, J. 1963. Some remarks on the distribution and availability of the Iceland North coast herring. *Rapp P.-v. Réun. Cons. Int. Explor. Mer.* 154: 73-82.
- Jakobsson, J. 1961. Some remarks on the distribution and availability of the North coast herring of Iceland. ICES Herring symposium, paper no. (mimeo).
- Jakobsson, J. 1980. Exploitation of the Icelandic spring and summer spawning herring in relation to fisheries management 1947-77. *Rapp P.-v. Réun. Cons. Int. Explor. Mer.* 177: 23-42.
- Jentoft, S., and Kristoffersen, T. 1989. Fishermen's co-management; the case of the Lofoten Fishery. *Hum. Organ.* 48:355-365.
- Johannes, R.E. 1978. Words of the Lagoon: Fishing and marine law in the Palau district of Micronesia. University of California press, Berkeley, 245 pp.
- Johannes, R.E. 1989. Traditional ecological knowledge: a collection of essays. Gland, Switzerland, IUCN, World Conservation Union, 77 pp.
- Jones, N.B. and Konner, M. 1989. !Kung knowledge of animal behaviour. In Johannes, R.E. [ed.] 1989. Traditional ecological knowledge: a collection of essays. Gland, Switzerland, IUCN, World Conservation Union, pp. 21-29.
- Kantrowitz, M., Horstkotte, E. and Joslyn, C. 1997. Answers to frequently asked questions about fuzzy logic and fuzzy expert systems. *Comp.ai.fuzzy*, November 1997. <ftp.cs.cmu.edu:/user/ai/pubs/faqs/fuzzy/fuzzy.faq>
- Kawasaki, T. 1992. Mechanisms governing fluctuations in Pelagic fish populations. *S. Afr. J. Mar. Sci.* 12: 873-879.
- Keenleyside, M.H.A. 1955. Some aspects of the schooling behaviour of fish. *Behaviour* 8(2-3):183-248.
- Keiser, R., D.E. Hay, C.W. Haegele, D.C. Miller and T.J. Mulligan. 1987. Hydroacoustic herring survey results and trawl catches from Hecate Strait, October 15 to November 5, 1984. G.B. REED Cruise GBR84C and M.V. CANADIAN #1 cruise CAN84-1. *Can. MS Rep Fish. Aquat. Sci.* 1917: 107p.
- Kew, M.J.E. and Griggs, J.R. 1991. Native Indians of the Fraser basin: towards of model of sustainable resource use. In A.H.J. Dorsey and J.R. Griggs [ed.] Perspectives on sustainable development in water management; towards agreement in the Fraser basin. Westwater research centre, University of British Columbia. Vancouver, B.C, pp.17-48.
- Knudsen, H.P. 1990. The Bergen Echo Integrator: an introduction. *Journal du Conseil International pour l'Exploration de la Mer*, 47: 167-174.
- Kosko, B. 1990. Fuzziness vs. probability. *Int. J. Gen. Sys.* 17 (2): 211-240.
- Kosko, B. 1993b. Fuzzy thinking: the new science of fuzzy logic. Publ. Hyperion, New York, USA. 318p.
- Krause, J. and J-G.J. Godin. 1994. Shoal choice in the banded killifish: effects of predation risk, fish size, species composition and size of shoals. *Ethology* 98:128-136.
- Krause, J., J-G.J. Godin and D. Rubenstein. 1998a. Group choice as a function of group size differences and assessment time in fish: the influence of species vulnerability to predation. *Ethology* 104: 68-74.
- Krause, J., Ruxton, G.D., and Rubenstein, D. 1998b. Is there always an influence of shoal size on predator hunting success? *J. Fish. Biol.* 52:494-501.
- Kremmerer, A.J. 1980. Environmental preferences and behavioural patterns of Gulf Menhaden (*Brevortia patronus*) inferred from fishing and remotely sensed data. p345-370. In Fish behaviour and its use in the capture and culture of fishes (Bardach, J.E., Magnuson, J.J., May, R.C., & Reinhart, J.M., eds). ICLARM Conference proceedings, Manila.
- Lambert, T. 1987. Duration and intensity of spawning in herring, *Clupea harengus*, as related to the age structure of the mature population. *Mar. Ecol. Prog. Ser.* Vol 39, No. 3: p209-220
- Landeau, L. and J. Terborgh. 1986. Oddity and the 'confusion-effect' in predation. *Anim. Behav.*, 34:1372-1380.

- Larkin, P.A. 1996. Concepts and issues in ecosystem management. *Reviews in Fish Biology and Fisheries* 6(2): 139-164.
- Larkin, P.A. and Walton, A. 1969. Fish school size and migration. *J. Fish. Res. Board. Can.* 26 (3): 1372-1374.
- Legendre, P. 1993. Spatial autocorrelation: trouble or new paradigm? *Ecology* 74:1659-1673.
- Levin, S.A. 1992. The problem of pattern and scale in ecology. *Ecology* 73 (6): 1943-1967.
- Levins, R. 1968. *Evolution in changing environments: some theoretical explorations*. Princeton, N.J.: Princeton Univ. Press. 120pp.
- Lima, S.L. and Dill, L.M. 1990. Behavioural decisions made under the risk of predation: a review and prospectus. *Can. J. Zool.*, 68: 619-40.
- Logerwell, E. A. and N. B. Hargreaves. 1996. The distribution of sea birds relative to their prey fish off Vancouver Island: opposing results at large and small spatial scales. *Fisheries Oceanography* 5:3/4; 163-175.
- Lutcavage, M. & Newlands, N. 1998. A strategic framework for fishery-independent aerial assessment of bluefin tuna. International Commission for the Conservation of Atlantic Tunas ICCAT Working Document. SCRS/98/75:1-4.
- MacArthur, R.H. 1955: Fluctuations of animal populations and a measure of community stability. *Ecology*, 36: 533-536.
- MacCall, A.D. 1976. Density dependence of catchability coefficient in the California sardine, *Sardinops sagax caerulea*, purse seine fishery. *Calif. Coop. Oceanic. Fish. Invest. Rep.* 18: 136-148.
- MacCall, A.D. 1990. *Dynamic geography of marine fish populations*. Washington Sea Grant, University of Washington press, Seattle. 135p.
- MacFarland, W.N. & Moss, S.A. 1967. Internal behaviour in fish schools. *Science* 156 (3772), 260-262.
- Mackinson, S. 1999a. Application of Heuristics and Fuzzy Logic to Natural Resource Modelling. Intelligent processing and manufacturing of materials conference, Hawaii, July 10th-15th 1999.
- Mackinson, S. 1999b. Variation in the structure and distribution of pre-spawning Pacific herring shoals in two regions of British Columbia. *J. Fish. Biol.* In press.
- Mackinson, S. 1999c. An adaptive fuzzy expert system for predicting structure, dynamics and distribution of herring shoals. *Ecol. Mod.* In press.
- Mackinson, S., M. Vasconcellos, K. Sloman, T.J. Pitcher and C.J. Walters. 1997b. Ecosystem impacts of harvesting small pelagic fish in upwelling ecosystems: using a dynamic mass-balance model. *Forage Fishes in Marine ecosystems*, Alaska Sea Grant Program, AK-SG-97-01: 731-749.
- Mackinson, S. and Newlands, N. 1998. Using local and scientific knowledge to predict distribution and structure of herring shoals. *ICES CM 1998:J11*, 18pp.
- Mackinson, S., Vasconcellos, M. and Newlands, N. 1999a. A New Approach to the Analysis of Stock-Recruitment relationships: 'model-free estimation' using fuzzy logic. *Can. J. Fish. Aquat. Sci.* 56: 686-699.
- Mackinson, S. and Nøttestad, L. 1998. Combining local and scientific knowledge. *Rev. Fish Biol. Fish.* 8(4): 481-490.
- Mackinson, S., Sumaila, R., Pitcher, T.J. 1997a. Bioeconomics and Catchability: behaviour of fish and fishers during stock collapse. *Fish. Res.* 31: 11-17.
- Mackinson, S., Nøttestad, L., Guénette, S., Pitcher, T.J., Misund, O.A. and Fernö, A. 1998. Distribution and behavioural dynamics of ocean feeding Norwegian spring spawning herring: observations across spatio-temporal scales. *ICES CM 1998:J12*
- Mackinson, S., Nøttestad, L., Guénette, S., Pitcher, T.J., Misund, O.A., Fernö, A. 1999b. Cross-scale observations on distribution and behavioural dynamics of ocean feeding Norwegian spring spawning herring (*Clupea harengus* L.). *ICES J. Mar. Sci.* in press.
- Magnhagen, C. 1993. Conflicting demands in gobies: when to eat, reproduce, and avoid predators. p79-90. In *Behavioural ecology of fishes* (Huntingford, F.A., & Toricelli, P., eds.) Proceedings of a conference held at the Ettone Majorana Centre for scientific culture, Erice, Italy, 30 September-5 October 1991. Harwood Academic Publishers, Switzerland.
- Maguire, J-J., Neis, B. and Sinclair, P.R. 1994. What are we managing anyway?: the need for an interdisciplinary approach to managing fisheries ecosystems. *ICES-CM-1994/T:48*
- Magurran, A.E. Gregarious goldfish. *New Scientist.*, 9 Aug, 32-33.

- Magurran, A.E and Higham, A. 1988. Information transfer across fish shoals under predation threat. *Ethology* 78: 153-158.
- Magurran, A.E. 1990. The adaptive significance of schooling as an anti-predator defence in fish. *Ann. Zool. Fennici*, 27: 51-66.
- Magurran, A.E. and T.J. Pitcher. 1987. Provenance, shoal size and the sociobiology of predator evasion behaviour in minnow shoals. *Proc. Roy. Soc. (Lond.) B* 229: 439-465.
- Magurran, A.E., Oulton, W. and T.J. Pitcher. 1985. Vigilant behaviour and shoal size in minnows. *Tierpsychologie* 67, 167-78.
- Major, P. 1978. Predator-prey interactions in two schooling fishes, *Caranx ignobilis* and *Stolephorus pupureus*. *Anim. Behav.* 26: 760-77.
- Mangel, M. 1982. Search effort and catch rates in fisheries. *European Journal of Operational Research* 11:361-366.
- Maravelias C.D., Reid D.G., and Swartzman G. 1997. Seabed substrate and water depth preferenda of prespawning herring (*Clupea harengus*). *Marine Ecology Progress Series* (submitted).
- Maravelias, C.D. and Haralabous, J. 1995. Spatial distribution of herring in the Orkney/Shetland area (northern North Sea): a geostatistical analysis. *Neth. J. Sea Res.* 34(4): 319-329.
- Maravelias, C.D. 1997. North Sea herring (*Clupea harengus*, L.) distribution in relation to environment: analysis of acoustic survey data (1992-1995). Ph.D. Thesis, University of Aberdeen, pp. 1-242.
- Maravelias, C.D. and Reid, D.G. 1995. Relationship between herring (*Clupea harengus* L.) distribution and sea surface salinity and temperature in the northern North Sea. *Scientia Marina*, 59(3-4): 427-438.
- Maravelias, C.D., and Reid, D.G. 1997. Identifying the effects of oceanographic features and zooplankton on prespawning herring abundance using generalized additive models. *Mar. Ecol. Prog. Ser.* 147: 1-9.
- Maravelias, C.D., Reid, D.G., Simmonds, E.J. & Haralabous, J. 1996. Spatial analysis and mapping of acoustic survey data in the presence of high local variability: geostatistical application to North Sea herring (*Clupea harengus*). *Can. J. Fish. Aquat. Sci.* 53, 1479-1505.
- Massé, J., Koutsikopoulos, C., Patty, W. 1996. The structure and spatial distribution of pelagic fish schools in multispecies clusters: an acoustic study. *ICES J. Mar. Sci.* 53: 155-160.
- Mathisen, O.A., Lemberg, N.A., Johnson, R.L. 1983. Hydroacoustic indices as input to dynamic management systems of fish stocks. *FAO Fish. Rep. No.* 300: 223-231.
- May, R.M. 1981. Models for two interacting populations. In *Theoretical ecology: Principals and Applications*, 2nd edn. (R.M. May, ed.), pp 78-104. Blackwell Scientific Publications, Oxford.
- May, R.M. 1983. *Stability and complexity in model ecosystems*. Princeton University press, Princeton, New Jersey, USA.
- McCarter, B., , D.E. Hay, P. Whither and R. Kieser. 1994. Hydroacoustic herring survey results from Hecate strait,, November 22- December 2, 1993. W.E. Ricker Cruise 93HER. *Can Manuscr. Rep. Fish. Aquat. Sci* 2248: 40p.
- McCarter, B., P. Whither, D.E. Hay, and R. Kieser. 1991. Hydroacoustic herring survey results from Hecate strait, December 3-15, 1990 W.E. Ricker Cruise 90HER2. *Can Manuscr. Rep. Fish. Aquat. Sci* 2108: 48p.
- McEachen, G. (Pers. comm). Department of Fisheries and Oceans, Comox, B.C, Canada
- McKeown, B.A. 1984. *Fish Migration*. Croom helm, Timber press, Portland Oregon, 224pp.
- McNeill, D. and P. Freiburger. 1993. *Fuzzy Logic*. Publ. Touchstone, New York. ISBN:0-671-73843-7, 320 p.
- McQuinn, 1997. Metapopulations and the Atlantic herring. *Rev. Fish. Biol. Fish.* (7): 297-329.
- Meech, J.A. and Kumar, S. 1995. A hypermanual on Expert Systems. V.5. Ed. Canadian Centre for Mineral and Energy Technology, Ottawa, Ont., Canada. 3200 ep (electronic pages)
- Melle, W., Røttingen, I., Skjoldal, H.R. 1994. Feeding and migration of Norwegian spring spawning herring in the Norwegian Sea. *ICES C.M.* 1994, R:9. 25pp.
- Mercer, M.C. 1982. Multispecies approaches to fisheries management advice. *Can. Spec. Publ. Fish. Aquat. Sci.* 59.
- Messieh, S.N., Powles, M. & Cote, G. 1979. Food and feeding of the Atlantic herring (*Clupea harengus* L.) in the Gulf of St. Lawrence and adjacent waters. Canadian Atlantic Fisheries Scientific Advisory Committee Research Document. Department of Fisheries and Oceans, Ottawa, Ontario. 79/15.

- Metcalfe, N. 1993. Behavioural causes and consequences of life history variation in fish. P205-217. In Behavioural ecology of fishes (Huntingford, F.A., & Toricelli, P., eds.) Proceedings of a conference held at the Ettone Majorana Centre for scientific culture, Erice, Italy, 30 September-5 October 1991. Harwood Academic Publishers, Switzerland.
- Michalsen, K., Godo, O.R., and A. Fernö. 1996. Diel variation in the catchability of gadoids and its influence on the reliability of abundance indices. J. Mar. Sci. 53:389-395.
- Milinski, M. 1979. An evolutionary stable feeding strategy in sticklebacks. Z. Tierpsychol. 51: 36-40.
- Milinski, M. 1987. Tit-for-tat in sticklebacks and the evolution of cooperation. Nature, Lond., 325: 433-437.
- Milinski, M. 1993. Predation risk and feeding behaviour. - Pp. 285-306 in: Pitcher, T.J. (Ed.) The Behaviour of Teleost Fishes, 2nd ed. Chapman and Hall, London & Sidney.
- Millinski, M. and Heller, R. 1978. Influence of a predator on the optimal foraging behaviour of stickleback *Gasterosteus aculeatus*. Nature, Lond., 275: 642-644.
- Millischer, L., Gascuel, D. 1998. Individual based modelling of fishing tactics. ICES CM 1998/J:14.
- Misund, O.A., A. Aglen, A.K. Beltestad and J. Dalen. 1992. Relationships between the geometric dimensions and biomass of schools. ICES J. Mar. Sci. 49:305-315.
- Misund, O.A. 1990. Sonar observations of schooling herring: school dimensions, swimming behaviour, and avoidance of vessel and purse seine. Rapp P.-v. Réun. Cons. Int. Explor. Mer. 189: 135-146.
- Misund, O.A. 1993a. Dynamics of moving masses: variability in packing density, shape and size among herring, sprat and saithe schools. ICES J. Mar. Sci. 50: 145-160.
- Misund, O.A. 1993b. Avoidance behaviour of herring (*Clupea harengus*) and mackerel (*Scomber scombrus*) in purse seine capture situations. Fisheries Research 16 (1993): 179-194.
- Misund, O.A. 1993c. Abundance estimation of fish schools based on a relationship between schools area and school biomass. Aquatic. Living. Resour., 1993, 6: 235-241.
- Misund, O.A. 1997. Underwater acoustics in marine fisheries and fisheries research. Reviews in Fish Biology and Fisheries 7:1-34.
- Misund, O.A. A. Fernö, T.J. Pitcher and B. Totland. 1997. Tracking herring schools with a high resolution sonar. Variations in horizontal area and relative echo intensity. ICES J. Mar. Sci. 54:
- Misund, O.A. and A. Aglen. 1992. Swimming behaviour of fish schools in the North Sea during acoustic surveying and pelagic trawl sampling. ICES J. Mar. Sci. 49: 325-334.
- Misund, O.A. and S. Floen. 1993. Packing density and structure of herring schools. ICES mar. Sci. Symp., 196:26-29.
- Misund, O.A., A. Aglen & Frønæs, E. 1995. Mapping the shape, size, and density of fish schools by echo integration and high resolution sonar. ICES. Journal of Marine Science 52, 11-20.
- Misund, O.A., A. Aglen, S.O. Johanessen, D. Skagen, B. Totland. 1993. (#104) Assessing the reliability of fish density estimates by monitoring the swimming behaviour of fish schools during acoustic surveys. ICES mar. sci. symp., 196: 202-206.
- Misund, O.A., Aglen, A., Hamre, J., Ona, E., Røttingen, I. Skagen, D., and. Valdemarsen, J.W. 1996a. Improved mapping of schooling fish near the surface: a comparison of abundance estimates obtained by sonar and echo integration. ICES. Journal of Marine Science, 53:383-388.
- Misund, O.A., J.T. Ovredal and M.T. Hafsteinsson. 1996b. Reactions of herring schools to the sound field of a survey vessel. Aquat. Living Resour., 1996, 9:5-11.
- Misund, O.A., Luyeye, N., Boyer, D., Coetzee, J., Clark. 1998. Characteristics of sardinella aggregations in Angolan waters. ICES CM/J:30 17 pages.
- Mohr, H. 1971. Behaviour patterns of different herring stocks in relation to ship and midwater trawl. In Modern fishing gear of the world, 3 pp 368-371. H. Kristjonsson [ed.] Fishing news books Ltd, Farnham, Surrey, England.
- Molloy, J. 1980. The assessment and management of the Celtic Sea herring stock. Rapp P.-v. Réun. Cons. Int. Explor. Mer. 177: 159-165.
- Morgan, M.J. & Colgan, P.W. 1987. The effects of predator presence and shoal size on foraging bluntnose minnows, *Pimephales notatus*. Environmental Biology of Fishes 20, 105-111.
- Morgan, M.J. 1988. The effect of hunger, shoal size and the presence of a predator on shoal cohesiveness in bluntnose minnows, *Pimephales notatus* Rafinesque. J. Fish. Biol 32: 963-971.

- Mundy, P.R., T.J. Quinn II, and R.B. Deriso. 1985. Fisheries dynamics: harvest management and sampling. Washington Sea Grant Program. WSG85-1.
- Mysak, L.A., W.W. Hsieh, and T.R. Parsons. 1982. On the relationship between interannual baroclinic waves and fish populations in the Northeast Pacific. *Biol. Oceano.* 2: 63-103.
- Nash, C.H., Richardson, J.S. and Hinch, S.G. 1999. Spatial autocorrelation and fish production in freshwaters: a comment on Randall et al. (1995). *Can. J. Fish. Aquat. Sci.* In press.
- Neill, S.R. and Cullen, J.M. 1974. Experiments on whether schooling by their prey affects the hunting behaviour of cephalopod predators. *J. Zool.* 172:549-569.
- Neilson, J.D. and Perry, R.I. 1990. Diel vertical migrations in marine fishes: an obligate or facultative process? *Advances in Marine biology*, 26:115-168.
- Neis, B. 1992. Fishers' ecological knowledge and stock assessment in Newfoundland. *Newfoundland Studies* 8(2) 155-178.
- Neis, B., Felt, L., Schneider, D.C., Haedrich, R., Hutchings, J. and Fischer, J. 1996. Northern cod stock assessment: what can be learned from interviewing resource users? DFO Atlantic Fisheries. Research document 96/45, 28 pp.
- Newlands, N. & Mackinson, S. 1999. Mesoscale distribution of herring shoals: modeling habitat preferences using heuristic rules. In preparation for 17th. Lowell Wakefield Symposium, Anchorage, Alaska.
- Niquen, M. 1986. Informe de la compañía de pesca de la M/P 'Rio Damuji' (Enero-15 Febrero 1986). Inf. Interni Inst. Mar Perú, Callao: 53pp (available from IMARPE PO Box 22, Callao, Perú).
- Nøttestad, L. 1998. Extensive gas bubble release in Norwegian spring spawning herring (*Clupea harengus*) during predator avoidance. *J. Mar. Sci.* 55:1133-1140.
- Nøttestad, L., Aksland, M., Beltestad, A., Fernö, A., Johannessen, A., Misund, O. A. 1996. Schooling dynamics of Norwegian spring spawning herring (*Clupea harengus* L.) in a coastal spawning area. *Sarsia* 80: 277-284.
- Nøttestad, L., Axelsen, B.E. 1999. Anti-predator behaviour of herring schools during killer whale attack. *Can. J. Zool.* In press.
- Nøttestad, L., Giske, J., Jens Chr. Holst and G. Huse. 1999. A length based hypothesis to explain feeding migrations in pelagic fish. *Can. J. Fish. Aquat. Sci.* In press
- Nursall, J.R. 1973. Some behavioural interactions of spottail shiners (*Notropis hudsonius*), yellow perch (*Perca flavescens*) and northern pike (*Esox lucius*). *J. Fish. Res. Bd. Can.*, 30: 1161-1178.
- Odland, J. 1988. Spatial autocorrelation. Sage publications, London. 85p.
- Ohguchi, O. 1981. Prey density and selection against oddity by three-spined sticklebacks. *Adv. Ethol.*, 23: 1-79.
- Olla, B.L. and Davis, M.W. 1990. Behavioural responses of juvenile pollock, *Theragra chalcogramma* Pallas, to light, thermoclines and food: possible role in vertical distribution. *J. Exp. Mar. Biol. Ecol.*, 135:59-68.
- Olsen, K., J. Angell, F. Petterson. 1983. Observed fish reactions to a surveying vessel with special reference to herring, cod, capelin, and polar cod. *FAO Fish Rep.* 300: 131-138.
- Paloheimo, J.E., and L.M. Dickie. 1964. Abundance and fishing success. *Rapp. P-v. Réun. Cons. Int. Explor. Mer.* 155:152-163.
- Parr, A.E. 1927. A contribution to the theoretical analysis of the schooling behaviour of fish. *Occass. Papers Bingham Ocean. Coll.* (1): 1-32.
- Parrish, J.K. 1992. Do predators shape fish schools? Interactions between predators and their schooling prey. *Neth. J. Zool.* 42(2-3): 358-370.
- Parsons, L.S. and V.M. Hodder 1975. Biological characteristics of SW Newfoundland herring, 1965-71. *Int. comm. Northwest Atl. Fish. Res. Bull.* 11: 145-160.
- Partridge, B.L., Johansson, J. and Kalish, J. 1983. The structure of schools of giant bluefin tuna in Cape Cod bay. *Env. Biol. Fishes.* 9: 253-262.
- Partridge, B.L. and T.J. Pitcher. 1980 The sensory basis of fish schooling - the relative roles of lateral line and vision. *Journal of Comparative Physiology* 135: 315-325.
- Partridge, B.L. 1978. Sensory aspects of schooling, 550pp. Dissertation, University of Oxford.
- Partridge, B.L. 1982. Structure and function of fish schools. *Scient. Am.*, 245: 114-123.

- Partridge, B.L., T. Pitcher, J.M. Cullen, and J. Wilson. 1980. The three dimensional structure of fish schools. *Behav. Ecol. Sociobiol.* 6:277-288.
- Pauly, D., Chistensen, V., Dalsgaard, J. and Froese, R. 1998. Fishing down marine food webs. *Science (Washington)* 279: 860-863.
- Petitgas, P. and B. Samb. 1998. On the clustered occurrence of fish schools along acoustic survey transects and its relation to population abundance. *ICES CM/J:5* 20 pages.
- Petitgas, P. and Levenez, J.J. 1996. Spatial organisation of pelagic fish: echogram structure, spatio-temporal condition, and biomass in Senegalese waters. *ICES J. Mar. Sci.* 53: 147-153.
- Pimm, S.L. 1979. The structure of food webs. *Theoretical Population Biology*, 16: 144-158. Journal article.
- Pinkerton, E. and Weinstein M. 1995. Fisheries that work. Sustainability through community based management. A report to the David Suzuki foundation, Vancouver, BC, Canada. 199pp.
- Pitcher, T.J. 1979. The role of schooling in fish capture. *Int. Comm. Explor. Sea CM 1979/B:5*: 1-12.
- Pitcher, T.J. 1983. Heuristic definitions of shoaling behaviour. *Animal Behaviour*, 31: 611-13.
- Pitcher, T.J. 1986. Predators and food are the keys to understanding fish shoals: a review of recent experiments. *Naturaliste Canadien* 113: 225-233.
- Pitcher, T.J. 1992. Who dares wins: the function and evolution of predator inspection behaviour in shoaling fish. *Neth. J. Zool.* 42(2-3): 371-391.
- Pitcher, T.J. 1995. The impact of pelagic fish behaviour on Fisheries. *Scientia Marina*. 59(3-4): 295-306.
- Pitcher, T.J. 1997. Fish shoaling behaviour as a key factor in the resilience of fisheries: shoaling behaviour alone can generate range collapse in fisheries. *Proceedings of the 2nd World Fisheries Congress*. Vol. 2:143-148.
- Pitcher, T.J. and Allan, J.R. 1990. Accurate spatial parameters and distribution of North Sea herring (*Clupea harengus*) shoals from digitised acoustic survey data. Department of Agriculture and Fisheries of Scotland, Marine Laboratory, Aberdeen. Research Report.
- Pitcher T.J. and A.E. Magurran. 1983. Shoal size, patch profitability and information exchange in foraging goldfish. *Anim. Behav.*, 31: 546-555
- Pitcher, T.J. and Parrish J.K. 1993. Functions of schooling behaviour in teleosts. In: *The Behaviour of Teleost Fishes*, 2nd ed., Ed. by T.J. Pitcher: Chapman and Hall, London & Sidney, 364-439.
- Pitcher, T.J. and Partridge, B.L. 1979. Fish school density and volume. *Marine Biology* 54: 383-394.
- Pitcher T.J. and Wyche, C.J. 1983. Predator avoidance behaviour of sand-eel schools: why schools seldom split. p193-204. In *Predators and Prey in Fishes* (Noakes, D.L.G., Linquist, B.G., Helfman, G.S., & Ward, J.A., eds), Junk, The Hague.
- Pitcher, T.J., Green, D., and Margurran A.E. 1986a. Dicing with death: predator inspection behaviour in minnow shoals. *J. Fish. Biol.* 28: 439-448.
- Pitcher, T.J., A.E. Magurran and J.I. Edwards. 1985. Schooling mackerel and herring choose neighbours of similar size. *Marine Biology* 86: 319-322.
- Pitcher, T.J., A.E. Magurran and I. Winfield (1982) Fish in larger shoals find food faster. *Behavioral Ecology and Sociobiology* 10: 149-151.
- Pitcher, T.J., A.E. Magurran and J.R. Allan. 1986b. Size segregative behaviour in minnow shoals. *J. Fish. Biol.* 29 (Suppl A.):83-95.
- Pitcher, T.J., B.L. Partridge and C.S. Wardle. 1976. A blind fish can school. *Science* 194: 963-965.
- Pitcher, T.J., Mackinson, S., Vasconcellos, M., Nøttestad, L., and Preikshot, D., 1998. Rapid appraisal of the status of fisheries for small pelagics using multivariate, multidisciplinary ordination. *Fishery Stock Assessment Models for the 21st Century*, Lowell Wakefield Symposium, Anchorage, Alaska, October 1997.
- Pitcher, T.J., Misund, O.A., Fernö, A., Totland, B and V. Melle. 1996. Adaptive behaviour of herring schools in the Norwegian sea as revealed by high resolution sonar. *ICES J. Mar. Sci.* 53:449-452.
- Pope, J.G. 1980. Some consequences for fisheries management of aspects of the behaviour of pelagic fish. *Rapp. P.-v. Reun. Cons. Int. Explor. Mer*, 177: 466-476.
- Radakov, D.V. 1960. Observations on herring during a voyage of a research submarine "Severyanka". (In Russian, Marine Laboratory, Aberdeen trans. No. 718,) *Byull. Okeanogr. Kom. Akad. Nauk. S.S.S.R.*, 6: 39-40.

- Radakov, D.V. 1961. Features of the defensive behaviour of schools of some pelagic fish. Trudy Instituta Morfologii Zhivotnykh AN SSSR, 39.
- Radakov, D.V. 1973. Schooling in the ecology of fishes. Israel programme for scientific translations, Wiley, New York, 173pp.
- Reichlin, O. and H. Bormann. 1980. Causes of the decline in the southern Baltic herring. Rapp P.-v. Réun. Cons. Int. Explor. Mer. 177: 154-158.
- Reid DG. 1995. Relationships between herring school distribution and sea bed substrate derived from RoxAnn. ICES Int. Symp. Fish. Plank. Acoustics, Aberdeen, Scotland.
- Reid, D.G., Williams, D., Gambang, A., and Simmonds, E.J. 1993. Distribution of North Sea herring and their relationship to the environment. ICES C.M./H:23. International Council for the Exploration of the Sea, Charlottenlund, Denmark.
- Reinventing Fisheries Management. 1996. Fisheries Centre Research Report Vol 4 (2). 84p.
- Resh, V.H. and Rosenberg, D.M. 1989. Spatial-temporal variability and the study of aquatic insects. Canadian journal of Entomology, 121: 941-963.
- Robertson, D.R., Sweatman, H.P.A., Fletcher, G.A. and Cleland, M.G. 1976. Schooling as a means of circumventing the territoriality of competitors. Ecology, 57: 1208-1220.
- Robinson, C.J. 1995. Food competition in a shoal of herring: The role of hunger. Mar. Behav. Physiol. 24(4): 237-242.
- Robinson, C.M. and T.J. Pitcher. 1989a. Hunger motivation as a promoter of different behaviours within a shoal of herring: selection for homogeneity in fish shoal? J. Fish. Biol. 35:459-460.
- Robinson, C.M. and Pitcher, T.J. 1989b. The influence of hunger and rations on shoal density, polarisation and swimming speed of herring (*Clupea harengus* L.). J. Fish. Biol., 35: 459-60.
- Robinson, C.J., F.V. Arenas and G.J. Gomez. 1995. Diel vertical and offshore-inshore movements of anchovies off the central coast of Baja California. J. Fish. Biol. 47:877-892.
- Rose, G.A. 1993. Cod spawning on a migration highway. Nature, 366: 458-461.
- Røttingen, I. 1990. A review of variability in the distribution and abundance of Norwegian spring spawning herring and Barents Sea capelin. Polar Research, 8: 33-42.
- Røttingen, I. 1992. Recent migration routes of Norwegian spring spawning herring. ICES CM 1992/H:18, 8 pp.
- Saila, S.B. 1996. Guide to some computerised artificial intelligence methods. In Megrey, B.A. and Moksness, E. (Eds.) Computers in Fisheries Research. Chapman and Hall, London, pp.8-37.
- Sampson, D.B. 1990. Fishing costs and the relationship between catch rates and fish abundance. Cemare-Rep. Pap. New. Ser. 40. 38pp. Centre for marine resource economics, School of economics, Portsmouth Poly., Locksway Road, Milton, Southsea, Hampshire. PO4 8JF. UK.
- Sampson, D.B. 1991. Fishing tactics and fish abundance, and their influence on catch rates. ICES J. Mar. Sci. 48(3):291-301.
- Sampson, D.B. 1992. Fishing technology and fleet dynamics: predictions from a bioeconomic model. Mar. Resour. Econ. 7(1):37-58.
- Sampson, D.B. 1993. Fishing tactics in a two species fisheries model. In Decision making by commercial fishermen, Fisheries Centre Research report 1993, vol 1(2): 19-23. Fisheries Centre, University of British Columbia.
- Saville, A. 1980. Discussion and conclusions of the symposium on the biological basis of pelagic fish stock assessment. Rapp P.-v. Réun. Cons. Int. Explor. Mer. 177: 513-517.
- Saville, A. and R.S. Bailey. 1980. The assessment and management of the herring stocks in the North sea and the west coast of Scotland. Rapp P.-v. Réun. Cons. Int. Explor. Mer. 177: 112-142.
- Schaaf, W.E. 1980. An analysis of the dynamic population response of the Atlantic menhaden, *Brevoortia tyrannus*, to an intensive fishery. Rapp P.-V. Réun. Cons. Int. Explor. Mer. 177: 243-251.
- Schneider, D.C. 1989. Identifying the spatial scale of density dependent interaction of predators with schooling fish in the southern Labrador current. Journal of Fish Biology, 35 (suppl. A): 109-115.
- Schneider, D.C. and J.F. Piatt. 1986. Scale-dependent correlation of seabirds with schooling fish in a coastal ecosystem. Marine Ecology Progress Series Vol. 32: 237-246.
- Schwarz, A.L. and G.L. Greer. 1984. Responses of Pacific herring, *Clupea harengus pallasi*, to some underwater sounds. Can. J. Fish. Aquat. Sci. 41(8):1183-1192.

- Schweigert, J.F. and M. Linekin. 1990. The Georgia and Johnstone straits herring bat fishery in 1986: Results of a questionnaire survey. Can. Tech. Rep. Fish. Aquat. Sci. 1721: 44pp.
- Sette, O.E. 1950. Biology of the Atlantic mackerel (*Scomber scombrus*) of North America. 2. Migration and Habitats. Fish. Bull. Nat. Mar. Fish. Serv. U.S., 51: 251-358.
- Shafer, W. 1955. Über das Verhalten von Jungheringsschwarmen im Aquarium. Arch. Fischereitechnik, 8: 1-29.
- Shaw, W., R. Tanasichuck, D.M. Ware and G.A. McFarlane. 1989a. Biological and species interaction survey of Pacific hake, sablefish, spiny dogfish and Pacific herring off the south-west coast of Vancouver Island, August 1987. Can. Manuscr. Rep. Fish. Aquat. Sci. 2027: 149 p.
- Shaw, W., R. Tanasichuck, D.M. Ware and G.A. McFarlane. 1989b. Biological and species interaction survey of Pacific hake, sablefish, spiny dogfish and Pacific herring off the south-west coast of Vancouver Island. F/V CALEDONIAN, August 12-25, 1986. Can. Manuscr. Rep. Fish. Aquat. Sci. 2012: 134 p.
- Shelton, P.A. and M.J. Armstrong. 1983. Variations in parent stock and recruitment in Pilchard and anchovy population in the Southern Benguela system, p.1113-1132. In G.D. Sharp and J. Csirke [eds.] 1983. Proceedings of the expert consultation to examine the changes in abundance and species composition of neritic fish resources. San José, Costa Rica, 18-29 April 1983. FAO Fish Rep. 291. Vol. 2 and 3. 1225 p.
- Shotton, R. and R.G. Randall. 1982. Results of acoustic surveys of the SWINS (NAFO Div 4WX) herring stock during Feb and July 1981. Can. Atl. Fish. Sci. Advis. Comm. Res. Doc. 82/44.
- Similä, T. and F. Ugarte. 1993. Surface and underwater observations of co-operatively feeding killer whales in northern Norway. Can. J. Zool. 71: 1494-1499.
- Similä, T., Holst, J. C., and Christensen, I. 1996. Occurrence and diet of killer whales in northern Norway; seasonal patterns relative to the distribution and abundance of Norwegian spring-spawning herring. Can. J. Fish. Aquat. Sci. 53:769-779.
- Sinclair, M and T.D. Iles. 1985. Atlantic herring distributions in the gulf of Maine - Scotian shelf area in relation to oceanographic features. Can. J. Fish. Aquat. Sci. 42:880-887.
- Sinclair, M., V.C. Anthony, T.D. Iles and R.N. O'Boyle. 1985. Stock assessment problems in the Atlantic herring (*Clupea harengus*) in the Northwest Atlantic. Can. J. Fish. Aquat. Sci. 42: 888-898.
- Sissenwine, M.P. and J.E. Kirkley. 1982. Fishery management techniques. Practical aspects and limitations. Marine Policy 6:43-57.
- Slotte, A. 1996. Relations between seasonal migrations and fat content in Norwegian spring spawning herring (*Clupea harengus* L.) ICES C.M. 1996/H:11
- Slotte, A. 1998. Patterns of aggregations in Norwegian Spring spawning herring (*Clupea harengus* L.) during the spawning season. ICES CM 1998/J:32. 10 pages.
- Slotte, A. 1999. Differential utilization of energy during wintering and spawning migration in Norwegian spring spawning herring. J. Fish. Biol. 54: 338-355.
- Slotte, A. and A. Johannessen. 1996. Exploitation of the Norwegian spring spawning herring (*Clupea harengus* L.) before and after the stock decline; towards a size selective fishery Proceeding from the 2nd World Fisheries Congress, Brisbane, Australia 1996.
- Smith, P.F. and Jamieson, A. 1986. Stock discreteness in herrings: a conceptual revolution. Fish. Res. 4: 223-234.
- Smith, R.J.F. 1997. Avoiding and deterring predators. In behavioural ecology of teleost fish (Godin, J.-G.J. [ed]) pp-163-190. Oxford: Oxford University press.
- Smith, R.L., Paul, A.J., and Paul, J.M.. 1986. Effect of food intake and temperature on growth and conversion efficiency of juvenile walleye pollock (*Theragra chalcogramma* Pallas): a laboratory study. J. Cons. Int. Explor. Mer., Vol. 42 pp. 241-253.
- Sogard, S.M. and Olla, B.L. 1993. Effects of light, thermoclines and predator presence on vertical distribution and behavioural interactions of Juvenile walleye pollock (*Theragra chalcogramma* Pallas). Journal of Experimental Marine Biology and Ecology, 167:179-195.
- Soria, M., F. Gerlotto, and P. Fréon. 1993. Study of learning capabilities of tropical clupeoids using an artificial stimulus. ICES mar. Sci. Symp, 196: 17-20

- Soria, M., P. Fréon, and F. Gerlotto. 1996. Analysis of vessel influence on spatial behaviour of fish schools using a multi beam sonar and consequences for biomass estimates by echo-sounder. *ICES J. Mar. Sci.* 53:453-458.
- Soria, M., Petitgas, P. and Bahri, T. 1998. On the size of fish schools and clusters: a spatial analysis of multibeam sonar images in the Mediterranean sea. *ICES CM/J:8* 15pp.
- Stephenson, R.L. and Kornfield, I. 1990. Reappearance of spawning herring on Georges Bank: population resurgence not recolonisation. *Can. J. Fish. Aquat. Sci.* 47, 1060.
- Stephenson, R.L., M.J. Power, W.H. Dougherty, D.J. Gordon, and J.B. Sochasky. 1990. Assessment of the 1989 4WX herring fishery. *Can. Stl. Fish. Sci. Advis. Comm. Res. Doc.* 90/50: 48 p.
- Stocker, M., V. Haist and D. Fournier. 1985. Environmental variation and recruitment of Pacific herring (*Clupea harengus pallasii*) in the Strait of Georgia. *Can. J. Fish. Aquat. Sci.* 42 (Suppl 1): 174-180.
- Strauss, S. 1997. Fishery decision overshadows scientists' debate. *The Globe and Mail*, 6th September 1997.
- Street, N.G., Magurran, A.E. and Pitcher, T.J. 1984. The effects of increasing shoals size on handling time in goldfish, *Crassius auratus*. *J. Fish. Biol.*, 25:561-566.
- Stephenson, R. 1997. In-season management in the 4WX herring fishery. DFO Maritime Regional Fisheries Status Report 97/2E.
- Sugihara, G., and May, R.M.. 1990. Applications of fractals in ecology. *Trends in ecology and evolution* 5: 79-86.
- Svetovidov, A.N. 1963. Fauna of USSR fishes. Vol 2. No.1 Clupeidae. (Israel program for scientific translations, Jerusalem).
- Tanasichuk, R.W, Ware, D.M, Shaw, W, and G.A. 1991. Variations in the daily ration and feeding periodicity of Hake (*Merluccius productus*) and Spiny dogfish (*Squalus acanthias*) off the west coast of Vancouver Island. *Can. J. Fish. Aquat. Sci.* 48: 2118-2128.
- Taylor, F.C.H. 1984. Distribution and abundance of herring and other pelagic fish off the west coast of Vancouver Island in September, 1981. *Can. Tech. Rep. Fish. Aquat. Sci.* No. 1333: 48pp.
- Taylor, F.H.C. 1971. Offshore distribution of Pacific herring (*Clupea pallasii*) on basis of records from fur seal stomachs. *J. Fish. Res. Board Can.* 28: 1663-1665.
- Taylor, F.H.C. 1969. The British Columbia offshore herring survey Fisheries Research Board of Canada, No. 140, September 1969: p20-54.
- Tester, A.L. 1938. What time of day are herring caught? *Fish. Res. Bd. Can. Pac. Prog. Rep.* 36:5-6.
- Thorne, R.E. 1977. Acoustic assessment of Pacific hake and herring stocks in Puget Sound, Washington and Southeastern Alaska. *Rapp P.-v. Réun. Cons. Int. Explor. Mer.* 177: 265-278.
- Turner, G.F. and Pitcher, T.J. 1986. Attack abatement: a model for group protection by combined avoidance and dilution. *American Naturalist* 128: 228-240.
- Ulltang, Ø. 1976. Catch per unit effort in the Norwegian purse seine fishery for Atlanto- Scandian (Norwegian spring spawning) herring. *FAO Fish. Tech. Pap.* 155: 91- 101.
- Ulltang, Ø. 1980. Factors affecting the reaction of pelagic fish stocks to exploitation and requiring a new approach to assessment and management. *Rapp P.-v. Réun. Cons. Int. Explor. Mer.* 177: 489-504.
- Vabø, R. and Nøttestad, L. 1997. An individual based model of fish school reactions: predicting antipredator behaviour as observed in nature. *Fisheries Oceanography.* 6:155-171.
- Valdemarsen, J.W., and Misund, O.A. 1994. Trawl designs and techniques use by Norwegian research vessels to sample fish in the pelagic zone. The sixth Norwegian-Russian symposium, Precision and relevance of pre-recruit studies for fishery management related to fish stocks in the Barents Sea and adjacent waters, Bergen 14-17 June 1994. Paper 3.1 17pp.
- Van Havre, N. and FitzGerald, G.J. 1988. Shoaling and kin recognition in the three spined stickleback (*Gasterosteus aculeatus* L.). *Biol. Behav.* 13: 190-201.
- Videler, J.J. and C.S. Wardle. 1991. Fish swimming stride by stride: speed limits and endurance. *Reviews in fish biology and fisheries*; 1:23-40.
- Vignaux, M. 1996. Analysis of spatial structure in fish distribution using commercial catch and effort data from the New Zealand hoki fishery. *Can. J. Fish. Aquat. Sci.* 53: 963-973.
- Walters, C. and Maguire, J.J. 1996. Lessons for stock assessment from the northern cod collapse. *Reviews in Fish Biology and Fisheries* 6, 125-137.

- Walters, C., V. Christensen, D. Pauly. 1997. Structuring Dynamic Models of Exploited Ecosystems from Trophic Mass-Balance Assessments. *Rev. Fish. Biol. Fish.* 7(2): 139-172.
- Walters, C.J. and A. Parma. (1996). Fixed harvest strategies for coping with effects of climate change. *Can. J. Fish. Aquat. Sci.* 53:148-158
- Walters, C.J., M. Stocker, A.V. Tyler and S.J. Westrheim. 1986. Interactions between Pacific cod (*Gadus macrocephalus*) and herring (*Clupea harengus pallasii*) in the Hecate Strait, British Columbia. *Can. J. Fish. Aquat. Sci.* 42 (Suppl 1): 127-137
- Ware, D.M. 1985. Life history characteristics, reproductive value, and resilience of Pacific herring (*Clupea harengus pallasii*). *Can. J. Fish. Aquat. Sci.* 42 (Suppl 1):127-137.
- Ware, D.M. 1990. Climate, predators and prey: behaviour of a linked oscillating system. p279-292. In T. Kawasaki et al. [eds.] Long term variability of pelagic fish populations and their environment. Proceedings of the International Symposium. Pergamon press, Oxford.
- Ware, D.M. and G.A. McFarlane. 1989. Fisheries production domains in the Northeast Pacific ocean. p.359-379. In R.J. Beamish and G.A. McFarlane [eds.] Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models. *Can. Spec. Publ. Fish. Aquat. Sci.* 108.
- Ware, D.M. and R.W. Tanasichuck. 1989. Biological basis of maturation and spawning waves in Pacific herring (*Clupea harengus pallasii*) females. *Can. J. Fish. Aquat. Sci.* 46: 1776-1784.
- Warwick, C.J., Mumford, J.M. and Norton, G.A. 1993. Environmental management expert systems. *J. Env. Man.* 39:251-270.
- Weih, D. 1973. Hydromechanics and fish schooling. *Nature, Lond.*, 241: 290-291.
- Weih, D. 1975. Some hydrodynamical aspects of fish schooling, in Symposium on Swimming and Flying in Nature (eds T.Y. Wu, C.J. Brokaw and C. Brennan), Plenum Press, New York, pp. 703-718.
- Weiss, J.A. 1976. Population responses to patchy environments. *Annual review of ecology and systematics* 7: 81-120.
- Wetly, J.C. 1934. Experiments in group behaviour of fishes. *Physiol. Zool.* 7:85-128.
- West-Eberhard, M.J. 1989. Phenotypic plasticity and the origins of diversity. *A. Rev. Ecol. Syst.* 20: 249-278.
- Wheeler, J.P. 1990. Newfoundland southeast coast herring - 1990 acoustic survey results. *Can. Atl. Fish. Sci. Advis. Comm. Res. Doc.* 90/55.
- Whitehead, P.J.P. 1985. King herring: His place among the clupeoids. *Can. J. Fish. Aquat. Sci.* 42 (Suppl 1): 3-20.
- Wilson, B. (Pers. comm). Coastwide, Delta, BC. Canada.
- Winters, G.H. 1977. Migrations and activity levels of overwintering Atlantic herring (*Clupea harengus* L.) along south-west Newfoundland. *Journal of the Fisheries Research. Board of Canada*, 34:2369-2401.
- Winters, G.H. and J.P. Wheeler. 1985. Interaction between stock area, stock abundance and catchability coefficient. *Can. J. Fish. Aquat. Sci.* 42 (Suppl 1): 989-998.
- Winters, G.H., E.L. Dalley and J.A. Moores. 1985. Fortuity disguised as fisheries management: The case of Fortune Bay herring. *Can. J. Fish. Aquat. Sci.* 42 (Suppl 1): 263-274.
- Wood, H. 1930. Scottish herring shoals: pre-spawning and spawning movements. Fisheries, Scotland, Scientific Investigations, 1930, I.
- Zadeh, L.A. 1965. Fuzzy sets. *Information and Control.* 8 (3): 338-353.
- Zadeh, L.A. 1973. Outline of a new approach to the analysis of complex systems and decision processes. *IEEE transactions on systems, man and cybernetics*, Vol SMC-3, No. 1. January 1973.
- Zafermann, M.L. 1995. On the fine structure of fish concentrations. *Vopr. Ikhtiol.* Vol 35(1): 28-33.

Appendices

APPENDIX 2.1.1 Acoustic settings

1. Echosounder

Range of 0-500 m; Max.power: 4000 W; Time Varied Gain: 20 logR; Pulse length: 1 ms; Bandwidth: wide; Angle sensitivity: 21.9; 2-way beam angle: -21.0 dB; Sv transducer gain:- 25.0 dB; TS transducer gain: 24.9 dB; 3dB beam width: 7.0 dB; S_A recordings per nautical mile were averaged over a five nautical miles distance. Echo sounder recordings were presented in echograms.

2. Sonar

TX power: max; Range: 600 m; Pulse: FM auto; Gain: 9; Display gain: 9; Time Varied Gain: 30log R; AGC: weak; Normalisation: weak; Ping-to-ping filter: weak.

3. HP 9000 workstation school detection system

Minimum range: 50 m; Maximum range width 5 m; Minimum interval 5 m; Minimum detection pings: 4.

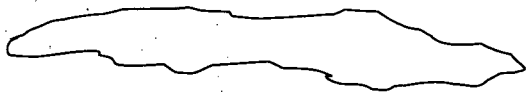
APPENDIX 2.1.2 School tracking

School 6 10:4:97

Video:2.36.35-3.44.04

Start 01:24. 2 distinct schools, depth 153m Range 130m. Several small dense targets visible close to the school. Area 800-900m². Other small schools in close vicinity

01:28 A school joins. School structure seems to be looser now. Larger area but lower density. School fragmenting whereas nearby school seems to be increasing. Pseudopodium visible. Joining. First school now dispersed. New school very elongated. School heading north



01:34 A different school appears on the echosounder

01:38 Depth 163m. School fragmenting? Maybe change in direction is causing poor aspect angle for visibility

01:41 Found again, 167m deep

01:43 Fairly circular. Dense, 15m deep. This is a different school

01:53 Turning vessel to improve the aspect angle. Now have a better view of the school

01:56 Back to the larger elongated school. It is about 50m from the other. Depth 167m

01:59 School joined from below. Original school becoming more elongated. Depth range 115-185m

02:04 2 schools appear on top right of the screen. Now there are three schools close together. Top 2 found to be connected.

02:16 Appeared to fragment - changed boat direction and school appeared clearly again

02:29 End. Travelled 500m in 1 hr = 0.14 m/s

APPENDIX 2.1.3 Descriptions of behavioural events (from Pitcher et al. 1996)

Behavioural events were defined as a change in school status and recorded when they became evident to the observer. Events were recorded in two categories: inter-school events and intra-school events. The seven intra-school behaviour events were as follows. *Compact*: an increase in density and reduction in area of a school, over a time span of 1-2 min. *Reorganize*: rapid internal re-arrangement of school sub-groups over a time span of 2-5 min. *Ring*: annular school structure, with a vacuole, or up to 3/4 of a vacuole, in the centre. *Pseudopodium*: elongated school sub-group extending out from the main body, often joining two globular school subgroups. *Elongate*: elongated main school, more than three times as long as broad, generally in the direction of swimming. *Dive*: rapid increase in school depth in less than 1 min. *Surface*: rapid decrease in school depth moving towards the surface. Four inter-school behaviour events were: *Approach*: continued move towards another school target by the focal school, or an approach by another school. *Join*: coalescence of two schools. *Leave*: small target, >10% of main group size (herring sub-group, or possibly predators) leaving focal school. *Split*: fission of one school into two, generally entailing two sub-groups emerging as schools over a time frame of 1-3 min.

APPENDIX 2.1.4 Institute of Marine Research biology codes for fish data.

Four parameters are measured and scored according to a numeric scale. Scores are collected in a database.

Parameter				
Scale	Fat	Sex	Stage	Stomach content
1	Nothing	Male		Empty
2	Small	Female	Immature	Small amount - open stomach to find it
3	More		Maturing	Medium - clearly see content
4	A lot		Maturing	Full
5	Can't see gut for fat		Maturing	Distended - food visible through lining
6			Spawning	Food expelled
7			Spent	
8			Recovering	

APPENDIX 5.1 Instructions on operating CLUPEX

(Readme.doc available on CD-rom)

CLUPEX and the Knowledge-base

For Help, Contact: Steven Mackinson
Email: smackin@fisheries.com

This Readme file contains all the information required to run, query and examine results from CLUPEX and to view the Knowledge-base

Getting started

Required: Windows 95 or higher

Follow the steps A-D for getting started

A. Set screen resolution

1. From the Windows Taskbar, press START. Go to Settings - Control Panel. Double click on Display and select the Settings tab
2. Set the desktop / screen resolution to 800 x 600, High Colour, Small fonts.
3. You will probably be asked to restart your computer before the settings take effect

B. Copy files from the CD-rom

4. Browse the contents of the CD-rom using windows explorer or through 'My computer' located on the desktop
5. In addition to the Readme.doc file you are currently reading, you will find the folder "CLUPEX-files"
6. Select the folder
7. Hold the control key down and drag it on to the desktop (this creates a copy of the files on your desktop)/ or use copy and paste in windows explorer to place it on the desktop

C. Create shortcuts on the desktop

8. Open the CLUPEX-files folder. Select the file "Res_run.exe" (the one with the herring icon). Click the RIGHT mouse button and choose Create Shortcut. A shortcut to Res_run.exe will be created in the CLUPEX-files folder. To re-name the shortcut, select it, click on the RIGHT mouse button and choose Rename; enter the name "CLUPEX"
9. To create a shortcut to the Knowledge-base, select the file "Knowledge.mde", RIGHT click and Create Shortcut. Rename the shortcut "Know-B" (You can also change the icon by selecting it, RIGHT click, Properties - Shortcut - Change icon. Browse the "CLUPEX-files" folder and select the icon Arrow #3 icon file.
10. Either copy and paste or drag the two shortcuts to the Desktop. From now on you will be able to run CLUPEX and the Knowledge -base simply by double clicking on them.

CAUTION: do NOT re-name the "CLUPEX-files" folder. This will affect the operation of programs contained in it.

D. Create temporary folder for results files

11. If you do not already have one, you will need to create the folder c:\temp (if you do have one, then you are ready to go)
12. To create the folder c:\temp in windows explorer; select the c: drive, click File - New - Folder and then name the folder "temp".

Opening and operation (please select from below)



CLUPEX- operating



Knowledge-base- requirements, specifications and use

CLUPEX: about runtime sessions on the desktop

For steps to getting the most out of the runtime, click any blue topic below. Or, continue reading below for details about how runtime sessions work.

Operating a Runtime

Run a System on the Desktop

Answer a Multiple-Choice Question in a Runtime default screen

Enter a Value for a Variable in a Runtime default screen

Undo a Previous Answer

Change Your Responses and Rerun

Save and Recover User Input in a Runtime

Getting Information about a Run

Ask How a Runtime Result was Obtained

View a Rule in a Runtime

Ask Why a Question is Displayed

View All Known Data in a Runtime

Guide to Colour Coding for Rules in a Runtime

Input and Output files generated during a run

Run a System on the Desktop

To start a runtime:

1. Double click the CLUPEX shortcut icon. This will open the Resolver runtime program displaying the CLUPEX splash screen (if for some reason it does not, contact Steve Mackinson)
2. Select Open from the file menu and choose file CLUPEX.RB1. The file will open and you will be presented with the opening text. It is important that you MAXIMISE the screen at this point for the following screens to be displayed correctly.
3. Click the Run Expert System button on the title screen. The Starting Text screen containing introductory text will be displayed.
4. Click Continue.

5. Custom forms and default screens are displayed for you to enter required inputs. Notice that there are several buttons on the bottom of the forms:

EXIT - exits system

Known Info. - presents display of current Known data that can be queried in the middle of any run by using the HOW and SOURCE buttons

HELP - custom help to guide you through the questions and provides additional information

OK, all done - the OK button when you have finished entering data

Text highlighted in blue is HYPERTYEXT that leads to an description/ definition of that term.

Hypertext can be accessed by double clicking at any point where the text is highlighted blue.

Note on default screens:

For details about completing the Ask Question window, see Answer a Multiple-Choice Question in a Runtime. For details about completing the Ask Variable window, see Enter a Value for a Variable in a Runtime.

6. During the run, those rules that have been concluded as true are displayed in tiles in the back ground. Double clicking on the tile will allow you to view the rule and any associated notes and references.
7. After sufficient questions have been asked, the Ending Text screen is displayed.
8. Click Continue.
9. The Results window is displayed. The results window shows the values that you input together with the values predicted by the system. You can query the results to find out where they came from by selecting a result (highlighted by clicking on it) and pressing the HOW button. The rules that were used to make the conclusion will be displayed.
10. Click Done to display a prompt asking if you want to run the session again.

Note:

To cancel a run at any time during the run, click Options on the menu bar, then Cancel Run.

Answer a Multiple-Choice Question in a Runtime default screen

While you interact with the system, you may be asked to select from among two or more choices to answer a question.

To select one or more choice(s):

1. Click a choice to highlight it. Then, click OK. Or, double-click the choice.

NOTE:

Some questions allow only a single choice, others may allow multiple choices. The default question window seen by the user will indicate whether the system accepts a single or n number of choices.

If the screen only allows a single choice, clicking on another choice will de-select the first choice and select the second.

If the screen allows multiple choices, clicking on several will highlight each of them.

To de-select choice(s):

To de-select a highlighted choice, click on it again.

To "pass" on a question:

You cannot decline to answer a question. The knowledge-based system requires the requested information to continue processing. If you do not wish to continue, select Exit from the File menu; or, click Cancel Run from the Options menu. It is also possible to save the input already entered prior to exiting. See Save and Recover User Input in a Runtime.

Enter a Value for a Variable in a Runtime default screen

While you interact with the system during a runtime, you may be asked to enter typed information in a data entry field. This is to satisfy a value for a string or numeric variable.

To enter a value for a variable:

1. Enter the value in the box at the bottom of the window. (Numeric responses can contain commas, which will be ignored in converting the value. String variables are case-sensitive.)
2. Click OK.

To "pass" on a variable:

You cannot decline to enter a value. The knowledge-based system requires the requested information to continue processing. If you do not wish to continue, select Exit from the File menu; or, select Cancel Run from the Options menu. It is also possible to save the input already entered prior to exiting. See Save and Recover User Input in a Runtime.

Undo a Previous Answer

Sometimes while running a system, end users may want to change their answer to a previous question.

IMPORTANT NOTE:

This facility can ONLY BE USED to undo answers from default question screens. Custom form type screens contain multiple question that are not recognised by the order in which you may have answered them.

To undo a previous answer:

1. On the system menu bar during a run, click Question, then Undo Prev Answer.
2. The system re-asks the previous question (you are only allowed to 'back-up' once).

Change Your Responses and Rerun (option not presently available - contact Steve Mackinson for instructions if required)

CAUTION:

Be careful when using this facility – bugs have been found in the software such that this does not always work correctly – be sure to check thoroughly how you 'new' answers were derived. The system allows you to find out what will happen to results if you change some of the input. You can change one or more answers; rerun the data, and view the effect of changes on the final

results. You can also save the original confidence values for goals to compare with the new values.

After the system runs with the changed data, it will present the results in the Results window. However, recognising that you have made changes, the system displays the Results window with two columns of data: the original values, and the values obtained as a result of the modified data. This allows side-by-side comparison of your changes.

To activate change and rerun:

1. On the Results window, click Rerun.
The system displays all of the data you have provided.
2. Click an item to highlight it, then click Change. Or, double-click the item.
The system displays the Ask Question or Ask Variable window containing the item.
3. Select a new answer.
4. Repeat Steps 2 and 3 as necessary.
5. When you have finished modifying the data, click Rerun on the Results window. If the Ending Text window is displayed, click Continue.

The changed data may fire different rules that require additional data. After you click Rerun, the system may ask new questions. The system displays the Results window with new goals based on the change(s). However, this time the Results window will have two columns of data: the values obtained as a result of the modified data, and the original values (labelled "Prev").

To return to the original input:

On the Results window, click Original.

To cancel the rerun:

On the Results window, click Cancel.

Save and Recover User Input in a Runtime

The system provides the option of saving input data to a file, exiting before completing the program, and returning to the same point later. This option can be useful if you need to look up information for the program or must leave the program but do not want to lose the data already input.

To save the input:

1. On the menu bar during the runtime, click Question, then Save Input.
The system prompts you for the name of the file in which to save the data.
2. The filename may be any legal filename. (Take care not to overwrite system files. Using the name of the system itself is not recommended.) The file "savein.dat" already exists – use this one for the first time.

If a file with the same name already exists, the previous version will be erased and replaced with the new data. The system confirms that it has saved your responses in the location you specified. You may wish to write down this information.

3. After saving the input, you can safely finish the run and click Done, or exit the run by clicking Cancel Run.

To recover the input:

1. Reopen the system if it was exited, and access the Title Screen of the runtime.
2. On the menu bar during the runtime, click Question, then Recover Input. The system displays the Recover window.
3. In the Recover data from file? field, click Yes if the input you are recovering was saved to a file.
4. In the Specific file or ask at runtime? field, click File and provide the name of the file, if any, that contains the input. Or, click Ask if you want the runtime to display a prompt asking the end user to provide the filename.
5. Click OK.
The system reads in the saved data (if you clicked File) and continues processing.

Ask How a Runtime Result was Obtained

In most knowledge-based systems, the results are displayed at the end of a run. You can find out how the system arrived at a particular answer:

To ask how a result was obtained:

1. On the Results window, click the item to highlight it, then click HOW. Or, double-click the item. The system displays the Rule TRUE/FALSE window, showing the rule that led directly to the item's selection for display as a result. (See Guide to Colour Coding for Rules in a Runtime.)
2. Highlight an item in the IF Part of the rule, then click SOURCE to display the Note window describing how the system obtained the data that led to the THEN Part. Click OK or Cancel to close the Note window.
3. Click Prev and Next to view other rules in the system, and their impact on results.
4. Click Done to return to the Results window.

View a Rule in a Runtime

There are several situations where a rule might be displayed during a runtime:

1. Rules will display if you click the Why button on the Results window (see Ask Why a Question is Displayed), or highlight a question and click the Why option on the Question menu.

2. Rules will display if you click Display Rule from the Question menu.

To view a rule:

1. On the menu bar during a runtime, click Question, then Display Rule.
2. The system displays the Rule to Display window.
3. Double-click the name of the rule you want to view. Or, highlight it and click Display.

The system displays the Rule TRUE/FALSE window for the selected rule.

To interpret the meaning of the rules display, see Guide to Colour Coding for Rules in a Runtime.

To view details about the rule:

1. On the Rule TRUE/FALSE window, click a button:
2. Reference - provides special information about the rule.
3. Source - explains how the system acquired information to satisfy the selected IF Part of the rule (you must select an item in the IF Part before clicking the button).
4. Prev - displays the rule numerically prior to this one.
5. Next - displays the rule numerically following this one.
6. All rules have a note associated with them. Notes are used to provide additional information or to explain a complex rule.

Ask Why a Question is Displayed

The system will explain why a question is being asked. This results in the display of the rule that is currently being tested. If the data is needed because of backward chaining, there may be a series of rules displayed. There may also be some other explanation of why the question was asked.

To ask why a question or variable is being asked:

1. While the Ask Question or Ask Variable window is displayed, click the Question on the menu bar. Then, select Why.

The system displays the Rule window showing where this question or variable appears as a condition in the IF Part. In a backward chaining system, the THEN part will contain a goal or other data element for which the system is trying to set a value. See Guide to Colour Coding for Rules in a Runtime.

After displaying a rule, the program may either repeat the question originally asked or it may display another rule. Another rule is displayed if the first rule was only used to derive information needed by the second rule, and the second is the rule actually being tested. (One of the THEN conditions in the first rule will be in the second rule's IF conditions - this is backward chaining.) All of the questions asking for information about the rule are available. The program will continue showing the rules it is using to derive information until it reaches the base rule it is trying to test.

2. To view other rules, click Prev or Next.

For every additional instance in which this question or variable appears as a condition in the IF Part, the system displays the question and choice(s) or variable and value(s).

3. Click Done to return to the Ask Question or Ask Variable window.

If more than one rule was displayed, each time OK is selected, the program goes up one rule on the list being used in the derivation. Eventually, the program repeats the question originally asked. Enter a value and click on OK to continue the program execution.

View All Known Data in a Runtime

To view all data known to the system:

1. On the menu bar during the runtime, click Question, then Known Data.
The system displays the Known Data window listing all of the data known to the system for this run. If you keep the Known Data window active while the system is running, the system will dynamically add each new item of data to the window as it is provided by the user or derived from rules.
2. Double-click on an item on the Known Data window to view the source for the data. Or, use the HOW and SOURCE buttons.

Guide to Colour Coding for Rules in a Runtime

At the end of a runtime, you can view the rules, identify which fired during the run, and view which conditions were true or false. Use this guide to interpret the role of each rule in obtaining the final results of the run.

1. A condition displayed in RED is false, a condition displayed in BLACK is true and a condition displayed in BLUE is unknown.
2. The status of the rule (TRUE, FALSE or NOT TESTED) appears on the top line of the window.

(Note: "Not tested" may appear for a rule that is definitely true or false, it only indicates that the rule has not yet been used during the run. If this is the case at the end of a run, perhaps it is because the rule is not relevant to the goals in the system.)

The colour coding for the rules is updated as each new piece of data is added. If a rule is displayed during a run, it is easy to notice the colour change from BLUE to BLACK indicating the point at which it fired. The window title also displays if the rule is true, false or unknown.

Input and Output files generated during a run

Whilst operating the system creates 7 text based files and writes them to the C:\temp directory. Four files contain input and output information from the run that can be used to plot results or in reports. The obsolete files used only for displaying results are "qualscre.sc1, qualscre2.sc1 and tabdat.sc1". The four important files are:

1. Input.dat: file records the values input for the following input parameters (in order specified in table)

Qualifier/ Variable name	Description
TOD	Time of day
LPHASE	Life phase
FOODDEP	Food depth distribution
FPATASSOC	Food patches associated with specific ocean features
FPATDIST	Distance between food patches
FOODSZ	Size of food
PREDSP	Predator species
BIRDDIST	Distribution of birds
MATSTAGE	Pre-spawning maturation stage (British Columbia herring roe categories)
CURRDIR	Direction of current
TIDE	State of tide
FEATURES	Typical topography and substrate features are:
SPAWHAB	Area of available of spawning habitat
TEMP	Water temperature regimes
COMPET	Competition from other species
MOON	State of moon cycle
SIZECOMP	SIZE COMPOSITION OF FISH IN SHOAL
FISHDIR	FISH DIRECTION
STOCKSIZE	RELATIVE STOCK SIZE
IMPTOD	Importance of time of day
WEATHER2	Chose description that best describes the weather
LOCATION	Location
infood	Relative abundance of food on scale 0-10
inpred	Relative abundance of aquatic predators on scale 0-10
wdepth	Water depth (m)
currdepth	Relative current depth (%)
ageclass	Approximate number of age groups in the stock
avoid	Degree of vessel avoidance (%)
currstren	Current strength in knots 0-10

2. Shoalout.out: output file with values of quantitative descriptors. The file outputs the values shown in the sequence shown in the table below:

Variable name	Description
inputstock	Local abundance for area considered (t)
shoalsize	Mean shoal size (t)
shoalsizemin	
shoalsizemax	
packden	Mean packing density (fish per m ³)
packdenmin	
packdenmax	
shoaldepth	Relative depth (%): 100% is bottom
shoaldepthmin	
shoaldepthmax	
speed	Mean Shoal speed (ms ⁻¹)
speedmin	
speedmax	
dyntend	Dynamic tendency (behavioural events per hour)
dyntendmin	
dyntendmax	
catchease	Ease of capture (expected % success seine sets)
catcheasemin	
catcheasemax	
ISDmav	Mean of the average Inter-shoal distance (km)
ISDmavmin	
ISDmavmax	
NNDm	Mean Nearest neighbour distance (km)
NNDmmin	
NNDmmax	

3. Shoalout.qds: output file with values of qualitative descriptors. The file outputs the values shown in the sequence shown in the table below:

Qualifier name	Description
EXTENT	Relative extent/ area of shoal
INTDYN	Internal dynamics
SEGSIZE	Segregation of size classes
SHAPE	Shoal shape
COHESION	Shoal cohesion
FISHDIR	Fish direction with respect to current
STOCKSIZE	Relative stock size
STOCKRANGE	Stock fulfillment of range
DISTEXTENT	Stock distribution extent
SASSOC	Shoal association with specific physical/ oceanographic features
SMOVE	Shoal movements
LOCSHIFT	Likelihood of location shift
Q	Catchability
AQPREDATT	Attack rate of aquatic predators

4. Shoalout.hbt: file used to specify codes indicating occurrence of habitat types during visualization of shoals. Codes: 0-not present, 1: present, no association, 2: present and shoals associated. Codes are specified for the following habitat types (in order of sequence):

Variable name	Description
rockreef	Rock pinnacles/reef structure
frontal	Frontal zone
steepbluff	Bluffs of steep sided channels
hardbot	Hard bottom with rock outcroppings
softbot	Soft bottom with surface irregularities
passbay	Passes with high flushing rate and inlets and bays
spawnsub	Spawning habitat

Knowledge-base: examining the knowledge database

Requirements

The Knowledge-base is a database file constructed in Microsoft Access. The file is called "knowledge.mde". To view Knowledge-base you will require Microsoft Access 97 or higher.

Specifications and Use

To open the knowledge-base, double click on the Know-B shortcut or use MS Access to open the file knowledge.mde

The database contains detailed information on sources of quantitative and qualitative data used in developing CLUPEX. The information contained in the database is cross-referenced to CLUPEX using the specific ID#'s of references, interviews, and rules.

On opening the database you have option to EXIT, ENTER or Run CLUPEX.

Press ENTER: leads to the **Select Options** menu which has 3 tabs: (**NOTE:** at any point in the database you can use the 3 buttons on the left of each screen either to go BACK one step, go to the START, or EXIT)

1. View original data forms

Four options are presented: press on a button to choose an option

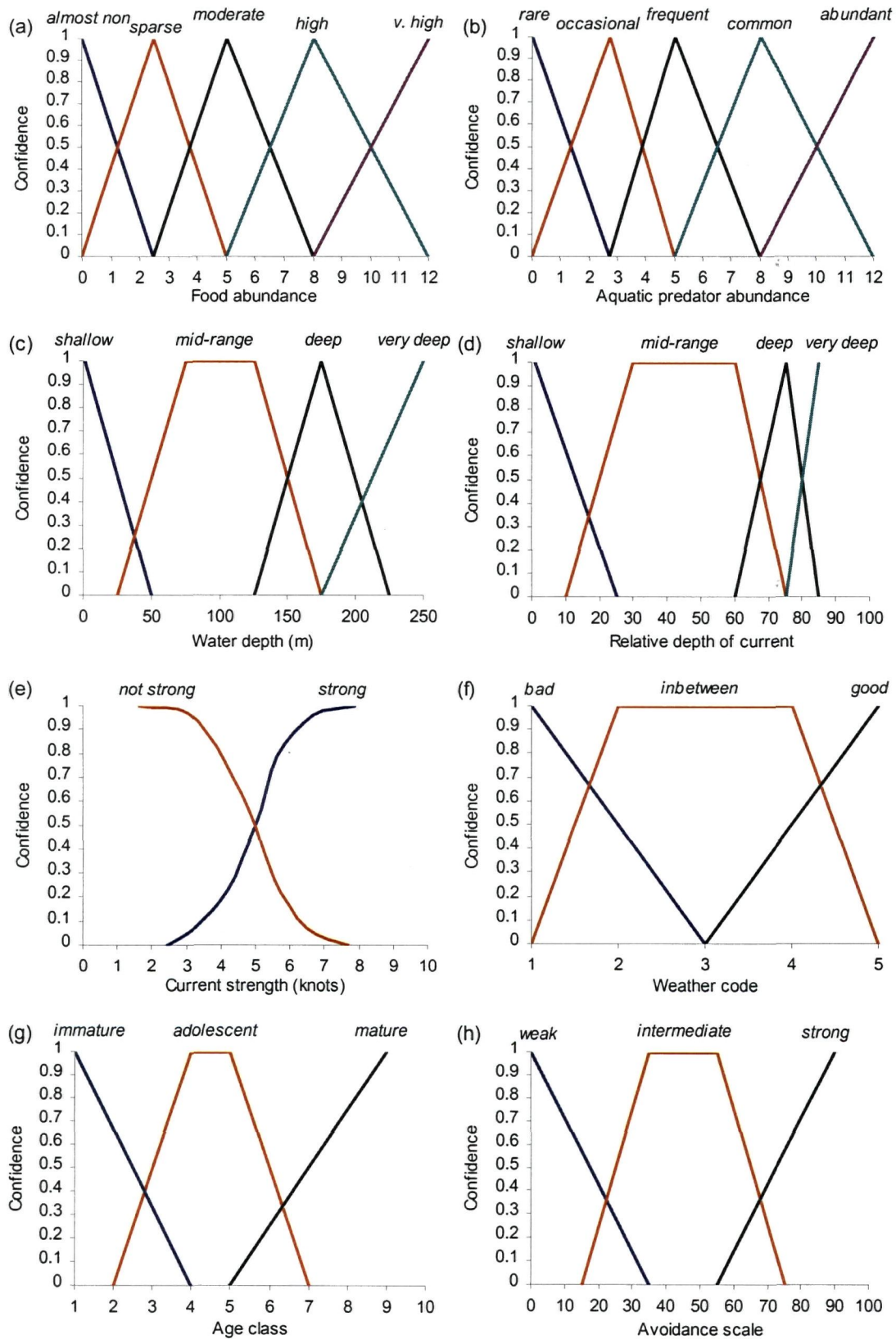
2. Questions and answers

Pre-selected summary tables of the database have been designed to help answer the most common queries

3. Make suggestions or add knowledge

The user can make suggestions in a notepad file (please remember to save it after making additions) and also to use custom form to contribute knowledge to the database

APPENDIX 5.2: Definitions of fuzzy variables used as input to CLUPEX



(a) Food abundance, (b) Aquatic predator abundance, (c) Water depth, (d) Relative depth of current, (e) Current strength, (f) Weather code, (g) Age class, (h) Avoidance scale

APPENDIX 5.3: Propagation of confidence

The confidence associated with specific output descriptors is set in one of three ways; taken as being unity when set by the user; determined by a fuzzy membership function for fuzzy attributes; if it is assigned a value in the THEN part, the confidence is propagated from the IF part and combined with any confidence in the THEN part.

Confidence in the IF part

The IF part may be made up of one or more conditions linked by AND or OR. Depending on whether the IF part is made up of only one condition or a single attribute value the confidence is simply the confidence associated with that condition or attribute. If there are more than one attribute values set using an OR such as; IF food abundance almost non OR sparse, we combine the confidence of 'food abundance almost non' and 'food abundance sparse', using the default formula:

$$\text{Combined conf.} = \text{combined conf.} + (\text{Value conf.} * (1 - \text{combined conf.}))$$

The formula is known as the MYCIN method (after the first system that used this method) and has the advantages that the confidence never exceeds 1, each positive confidence increases the final confidence, and it not sequence specific. The same method is used for combining the confidence of blocks of OR statements in the IF part of a rule. The overall confidence in the IF statement is calculated as the product of the parts. This simply means multiplying the combined confidence of conditions linked with an OR with those conditions linked with AND. By setting a threshold, rules are only considered to be true when the overall IF confidence is above 0.01.

Confidence in the THEN part

In the fuzzy system, when a rule fires, the IF part will be TRUE, meaning all the parts in the IF statement have a confidence >0. The final THEN confidence is achieved by multiplying the overall IF confidence with the confidence assigned in the THEN part and combining it with the current confidence by a series of formulas (again, the MYCIN method);

$$\text{Current conf.} = (\text{IF conf.} * \text{assigned THEN conf.}) + (\text{Curr. Conf.} * (1 - (\text{IF conf.} * \text{assigned THEN conf.})))$$

The formula has the characteristics that any positive value increases the final confidence, and when a THEN part has a low confidence, a high value significantly increases it, but when a THEN part has a fairly high confidence, additional high values only increase it slightly.

There is one important shortcoming in the use of the above formulas for propagating confidence. When the IF part has an overall confidence of 1, which occurs when a user directly chooses an attribute value (rather than it being calculated during inferencing) and this is combined with a THEN item whose assigned confidence is also 1, the final IF confidence is pushed immediately to 1. Thus, the confidence combined by firing of other rules has no apparent effect. The simple pragmatic solution used here is to ensure that all items in the THEN part are assigned confidence values <1.

APPENDIX 5.4 Input attribute values for general prediction tests

Table A 5.4.1 Input values for diurnal changes in overwintering Pacific herring.

Name	Value
TOD	VARIABLE
LPHASE	Overwintering
PREDSP	Fish AND sea lions and seals
MATSTAGE	Low importance
TIDE	Ebb
FEATURES	Soft bottom with surface irregularities (dips and trenches)
SIZECOMP	Mixture of small and large fish
FISHDIR	Facing current (Conf=.126)
STOCKSIZE	Medium
IMPTOD	Important
WEATHER2	Perfect calm and sunny
LOCATION	Pacific ocean
[infood]	Please indicate the relative abundance of food (scale 0-10) = 0.5
[inpred]	How common are aquatic predators (scale 0-10) = 4
[wdepth]	Approximate depth of the water in meters (note: 1 fathom is approx = 2m) = 150
[ageclass]	Approximate number of age groups in the stock = 8
[avoid]	Degree of avoidance to vessels (%) = 0
[currstren]	Approx strength of current in knots (0-10) = 2

Table A 5.4.2 Input values for ocean feeding Norwegian spring spawning herring.

Name	Value
TOD	Time of day Day (Conf=1)
LPHASE	Life phase ocean feeding (Conf=1)
FOODDEP	Food depth distribution shallow (Conf=1) AND mid-range (Conf=1)
FPATASSOC	Food patches associated with specific ocean features ocean front zone (e.g. temperature, currents, upwelling) (Conf=1)
FPATDIST	Distance between food patches low (Conf=1)
FOODSZ	Size of food small (Conf=1) AND large (Conf=1) AND medium (Conf=1)
PREDSP	Predator species Fish (Conf=1) AND whales and dolphins (Conf=1) AND small birds (Conf=1) AND large birds (Conf=1)
BIRDDIST	Distribution of birds not sure (Conf=1)
MATSTAGE	Pre-spawning maturation stage (British Columbia herring roe categories) low importance (Conf=1)
TIDE	State of tide ebb (Conf=1)
TEMP	Water temperature regime at location at a cold threshold (minimum temperature tolerance) (Conf=1)
COMPET	Competition from other species no competition (Conf=1)
SIZECOMP	SIZE COMPOSITION OF FISH IN SHOAL mixture of small and large fish (Conf=.1)
FISHDIR	FISH DIRECTION facing current (Conf=1)
STOCKSIZE	RELATIVE STOCK SIZE large (Conf=1) AND very large (Conf=1)
IMPTOD	Importance of time of day (special case of time in which to know answer) not important (Conf=1)
WEATHER2	Choose description that best describes the weather cloud and sun, maybe light showers (Conf=1)
LOCATION	Location Norwegian Sea (Conf=1)
[infood]	Please indicate the relative abundance of food (scale 0-10) = VARIABLE
[inpred]	How common are aquatic predators (scale 0-10) = VARIABLE
[wdepth]	Approximate depth of the water in meters (note: 1 fathom is approx = 2m) = 1000
[ageclass]	Approximate number of age groups in the stock = 12
[avoid]	Degree of avoidance to vessels (%) = 0
[currstren]	Approx strength of current in knots (0-10) = 2

Table A 5.4.3 Input parameters for seasonal changes in Pacific herring.

	Pre-spawn			Spawning	Immediate	Off-shore-	Ocean feeding			On-shore	Overwintering
	3 to 2	2 to 1	1		Post-spawn	migration	1	2	3	migration	
TOD	Day	Day	Day	Day	Day	Day	Day	Day	Day	Day	Day
LPHASE	Pre-spawning	Pre-spawning	Pre-spawning	Spawning	Imm-post-spawn	Off-shore	Ocean	Ocean	Ocean	On-shore	Overwintering
FOODDEP					Shallow and Mid-range	Mid range and deep	Mid range and deep	Shallow and Mid range	Mid range	Mid range and deep	
FPATASSOC							Frontal region	Frontal region	Frontal region		
FPATDIST					Medium	High	High	Low	Medium	High	
FOODSZ						All	All	All	All	All	
PREDSP	Fish AND sea lions AND small birds AND large birds	Fish AND sea lions AND small birds AND large birds	Fish AND sea lions AND small birds AND large birds	Fish AND sea lions AND small birds AND large birds	Fish AND sea lions AND small birds AND large birds	Fish AND whales AND dolphins AND small birds AND large birds	Fish AND whales AND dolphins AND small birds AND large birds	Fish AND whales AND dolphins AND small birds AND large birds	Fish AND whales AND dolphins AND small birds AND large birds	Fish AND whales AND dolphins AND small birds AND large birds	Fish AND sea lions AND small birds AND large birds
BIRDDIST	Concentrated patches	Concentrated patches	Concentrated patches	Concentrated patches	Scattered	not sure	concentrated	concentrated	concentrated	not sure	concentrated
MATSTAGE	3 to 2	2 to 1		1 Low importance	Low importance	Low importance	Low importance	Low importance	Low importance	Low importance	Low importance
CURRDIR						Driving food distribution				Not sure	
TIDE	Ebb	Ebb	Ebb	Ebb	Ebb	Ebb	Ebb	Ebb	Ebb	Ebb	Ebb
FEATURES	Steep sided channels AND soft bottom with Surface irregularities (dips and trenches)	Steep sided channels AND soft bottom with Surface irregularities (dips and trenches)	Steep sided channels AND soft bottom with Surface irregularities (dips and trenches)								Steep sided channels AND soft bottom with Surface irregularities (dips and trenches)
SPAWHAB				Medium AND large							
TEMP							Normal	Normal	Normal		
COMPET					No competition	No competition	No competition	Active	Active	No competition	
SIZECOMP	Mixture of small and large fish (CF= 0.1)	Mixture of small and large fish (CF= 0.1)	Mixture of small and large fish (CF= 0.1)	Mixture of small and large fish (CF= 0.1)	Mixture of small and large fish (CF= 0.1)	Mixture of small and large fish (CF= 0.1)	Mixture of small and large fish (CF= 0.1)	Mixture of small and large fish (CF= 0.1)	Mixture of small and large fish (CF= 0.1)	Mixture of small and large fish (CF= 0.1)	Mixture of small and large fish (CF= 0.1)
FISHDIR	facing	facing current	facing	facing current	not sure	running with	facing current	facing current	facing current	running with	facing current

	current (Conf=.126)	(Conf=1) AND not sure (Conf=1)	current (Conf=1) AND not sure (Conf=1)	(Conf=.128)	(Conf=1)	current behind (Conf=.01)	(Conf=1)	(Conf=1)	(Conf=1)	(Conf=1)	current behind (Conf=1) AND not sure (Conf=1)	(Conf=.126)
STOCKSIZE	Medium AND large	Medium AND large	Medium AND large	Medium AND large	Medium AND large	Medium AND large	Medium AND large	Medium AND large	Medium AND large	Medium AND large	Medium AND large	Medium AND large
IMPTOD	Not important	Not important	Not important	Not important	Not important	Not important	Not important	Not important	Not important	Not important	Not important	Not important
WEATHER2	Perfect calm and sunny	Perfect calm and sunny	Perfect calm and sunny	Perfect calm and sunny	Perfect calm and sunny	Perfect calm and sunny	Perfect calm and sunny	Perfect calm and sunny	Perfect calm and sunny	Perfect calm and sunny	Perfect calm and sunny	Perfect calm and sunny
LOCATION	Pacific ocean	Pacific ocean	Pacific ocean	Pacific ocean	Pacific ocean	Pacific ocean	Pacific ocean	Pacific ocean	Pacific ocean	Pacific ocean	Pacific ocean	Pacific ocean
[infood]		0.5	0.5	0.5	0.5	3	4	7	10	6	3	0.5
[inpred]		5	5	5	5	3	2	4	8	6	2	7
[wdepth]						150	500	500	500	500	500	200
[currdepth]							75				45	
[ageclass]		7	7	7	7	7	7	7	7	7	7	7
[avoid]		10	10	10	10	0	20	50	50	50	20	20
[currstren]		2	2	2	2	2	4	2	2	2	4	2

Table A 5.4.4. Input parameters for comparison with real data on pre-spawning Pacific herring.

TOD	Time of day Day (Conf=1)
LPHASE	Life phase pre-spawning (Conf=1)
PREDSP	Predator species Fish (Conf=1) AND sea lions and seals (Conf=1) AND whales and dolphins (Conf=1) AND small birds (Conf=1) AND large birds (Conf=1)
BIRDDIST	Distribution of birds concentrated patches (Conf=1)
MATSTAGE	Pre-spawning maturation stage (British Columbia herring roe categories) variable
TIDE	State of tide ebb (Conf=1)
FEATURES	Typical topography and substrate features are: steep sided channels (Conf=1) AND hard bottom with rock outcroppings (Conf=1)
SIZECOMP	SIZE COMPOSITION OF FISH IN SHOAL mixture of small and large fish (Conf=.1)
FISHDIR	FISH DIRECTION facing current (Conf=.126)
STOCKSIZE	RELATIVE STOCK SIZE small (Conf=1) AND medium (Conf=1)
IMPTOD	Importance of time of day (special case of time in which to know answer) not important (Conf=1)
WEATHER2	Choose description that best describes the weather windy and rainy (Conf=1)
LOCATION	Location Pacific ocean (Conf=1)
[infood]	Please indicate the relative abundance of food (scale 0-10) = .5
[inpred]	How common are aquatic predators (scale 0-10) = 3
[wdepth]	Approximate depth of the water in meters (note: 1 fathom is approx = 2m) = 80
[currdepth]	
[ageclass]	Approximate number of age groups in the stock (or oldest age to which fish live) = 8
[avoid]	Degree of avoidance to vessels (%) = 10
[currstren]	Approx strength of current in knots (0-10) = 2

APPENDIX A: CD-ROM - CLUPEX and Knowledge-Base