PAPER II

ON SAITHE (*Pollachius virens*) MIGRATIONS TO ICELAND

ABSTRACT

Past and present evidence of saithe migrations in the NE-Atlantic, with emphasis on those between Norway, the Faroe Islands and Iceland, is reviewed. A re-analysis of the only tagging experiment conducted at Iceland indicates that migration from Iceland to Norway is just as likely as migration in the opposite direction. Catch at age curves for a number of year classes of saithe at Iceland peak at a later age than normal, coincident with increased frequency of recaptures of Norwegian tags at Iceland and abnormally low mean lengths at age for the same year classes. Based on deviations in mean lengths at age and an application of the mixture model, the immigration of 7 year olds from the 1984 year class of the Northeast arctic saithe to the Icelandic stock is tenatively estimated at 3.5-7 million saithe or approximately 12-25 thousand tonnes.

1. Introduction

Although the Icelandic shelf waters can generally be regarded as an independent and well defined ecosystem with self-sustained stocks for many of the major commercial fish species, fisheries biologists working there have to take into consideration the possibility of interactions with other ecosystems.

The migrations of the Norwegian spring spawning herring, the main part of the Atlanto-Scandian herring complex, are a case in point and of special current interest. The presence of Norwegian herring at Iceland was first suggested in the 1930s (Friðriksson 1944) and later verified by tagging experiments (Friðriksson and Aasen 1952). In the 1950s and 1960s, the adult part of this potentially largest herring stock in the world migrated annually, after spawning off the west coast of Norway in February-March, across the Norwegian Sea to feed in the shelf waters off East- and North-Iceland and in the area between Jan Mayen and Iceland. At the end of the feeding season these herring assembled in an area some 40-80 nautical miles east of Iceland, where they remained until the onset of the return migration to their spawning grounds off Norway. Due to environmental adversities, this migration pattern was disrupted in the late 1960s, which, coupled with overfishing, led to the collapse of the stock (Dragesund *et al.* 1980). At present this herring stock is recovering and the adult biomass is estimated to be in the range of 3-4 million tonnes. Concurrent with this, the stock has again begun to migrate west across the Norwegian Sea in search of food in spring and summer. In 1994 and 1995 the feeding migration reached the eastern border of the East Icelandic Current, but continued north and northeast along the Polar Front. A further increase of the adult stock biomass is expected in the coming years with the recruitment of the 1991 and 1992 year classes (Anon. 1995a). When that happens, the earlier migration pattern might be re-established, with overwintering east of Iceland instead of in the Lofoten area, where the herring have spent the winter since the 1970s. The direct impact of several million tonnes of herring on the Icelandic marine ecosystem in the future is not clear but must be considerable.

Among the gadids, both export of fish larvae from the Icelandic area and immigration of older fish returning later to spawn are known occurrences. For cod, the drift of larvae to Greenland (Jensen 1926; Sæmundsson 1934; Vilhjálmsson and Magnússon 1984) and a migration returning to spawn at Iceland have been documented (Tåning 1937; Jensen 1939; Jónsson 1996) and to some extent quantified (Schopka 1993; Anon. 1992;

Stefánsson 1992; Shepherd and Pope 1993). The Greenland migration has at times given a considerable boost to the Icelandic cod stock, the record being the case of the migration of the 1945 year class, which is estimated to have added more than half a million tonnes to the Icelandic stock as 8 year old cod in 1953. Presently, however, there is no hope of even a small migration, due to record low abundance of cod at Greenland. (Anon. 1995b).

It has been established from recaptures of tagged fish, that the saithe, *Pollachius virens* L., are highly migratory and abundant evidence exists of a connection between the various stock units inhabiting the NE-Atlantic. This has been demonstrated for the Icelandic and Northeast arctic saithe stocks (Schmidt 1958; Olsen 1961; Jones and Jónsson 1971; Reinsch 1976; Jakobsen and Olsen 1987; Anon 1992; Bjørke and Sætre 1994; Anon. 1995c; Nedreaas and Smedstad 1995) with years when there have been signs of a significant migration of mature or maturing fish from Norway to Iceland (Schmidt 1958; Olsen 1961; Jakobsen and Olsen 1987). Furthermore, Olsen (1959) has suggested that these migrations are linked to the migrations of the Norwegian spring spawning herring, *i.e.* that the saithe cross the Atlantic while hunting herring. Indeed, the question of whether saithe travel from Norway to the saithe spawning grounds at the Faroes and at Iceland was part of the motivation for the first saithe tagging experiment, carried out in northern Norway in 1921 (Sund 1925).

To further investigate the topic of interactions between the saithe stocks in the NE-Atlantic, the literature on tagging and migrations of saithe and the drift of saithe larvae in this area was reviewed.

In the following, it will be established that the mean lengths at age of the Northeast arctic and the Icelandic saithe populations are different. It should therefore, in theory, be possible to detect an immigration of saithe from Norway, if one has sufficient knowlegde of its time and place of arrival. For the sake of simplicity, the main emphasis was put on the Icelandic and Northeast arctic saithe stocks, although it is clear that the Faroe saithe also enter these relations (cf. Section 2.1 on tagging experiments).

The age-length database and virtual population analysis (VPA) tables for saithe at Iceland were examined for signs of immigration. In order to identify potential migration events, differences in size at age between areas, variations in mean length at age (MLA) from spring survey data and on a quarterly basis from samples of the commercial catch, as well as variations in the mean weight at age used in VPA assessments, were studied (Anon. 1995b).

Furthermore, an analysis of published data from VPA of the Icelandic saithe dating back to the 1960s (Anon. 1993) revealed indications of a migration, in addition to those noted in a report by the North Western Working Group (NWWG) of the International Council for the Exploration of the Seas (ICES) (Anon 1992).

Finally, we go one step further and assume, for the sake of argument, that saithe from Norway or from other areas outside Icelandic waters are in part responsible for the, at times, considerably reduced MLA of the saithe at Iceland. The mixture model (*e.g.* James 1978; Shepherd and Pope 1993) was applied to the 1984 year class, the proportion of immigrants in the Icelandic area in 1991 was estimated along with the variance of that estimate.

2. Review of evidence of saithe migrations

2.1. Tagging experiments

A summary of the tagging experiments on saithe in the NE-Atlantic that have been reported is given in Table 2.1.

Table 2.1. Summary of saithe tagging experiments in the NE-Atlantic

Conducted by	Reported in	Tagging locality	Period of tagging	Number of tags	Tag returns
Norway	Reviewed by Jakobsen 1995	Norway	1921 and 1954-1982	87 000	≈15% overall recapture rate
Norway	Bjordal and Skar 1992	West coast of Norway	Nov. 1990 - Nov 1991	2 607	334 or 12.8% by June 1992
Faroes	Nicolajsen 1995	Faroes	1960-1965, 1976 and 1991	12 597	1 098 with known position or 8.7%
Iceland and England	Jones and Jónssson 1971	Iceland	In July of 1964 and 1965	6 000	3 175 or 52.9%
Scotland	Newton 1984	N. North Sea and W. of Scotland	1973-1988	4 658	310 or 6.7%
England	Jones and Jónsson 1971	Various localities	prior to 1964	unknown	393 with known position
France	Fontaine *et al.* 1985	N. North Sea and W. of Scotland	1980 and 1983	1 752	326 or 18.6%
				More than 115 000 saithe tagged	More than 18 500 tags recovered

Recapture rates in these tagging experiments vary a great deal. The tag releases north of Iceland in 1964 and 1965 had the singularly highest return rate, over 50%, while returns from the other experiments were more similar, ranging from 5-20%.

Table 2.2 summarizes recaptures from a part of the experiments above. The overview is incomplete, since the results of the experiments are given in varying detail and can not be directly compared. Furthermore, the Scottish and French experiments, conducted in the northern North Sea and west of Scotland, yielded no returns outside of the general area of tagging, other than from across the North Sea off the west coast of Norway and from the Norwegian Deep.

Table 2.2. Summary of recaptures of tagged saithe according to release and recapture locality.

	Recapture locality							
Tagging locality	Iceland	Faroes	North Sea	Mid-Norway	Norway north of 67°N	Tagging period	Notes	Source
Iceland	3 155	8	3	6	?	1964-1965	a	2)
Faroes	116	1 080	48	13	?	1960-65, 1976, 1991	a	2), 9)
North Sea	4	11	879	86	11	Prior to 1964, 1972-74		2), 3)
Mid-Norway	2	14	207	685	42	1971-74		4), 6)
Mid-Norway	0	4	59	236	9	1975-77		7)
Norway north of 69°30'N	106	50	?	388	?	1954-80	b	8)
Norway north of 69°30'N	20	6	?	?	?	1955-58	c, d	1)
Norway north of 67°N	6	5	35	20	1 055	1970-74	e	5)
Norway north of 67°N	2	5	29	90	1 161	1975-77	e	8)

a No distinction between Mid- and northern Norway.
b Reference 8) gives an analysis of the Norwegian taggings from 1954-1980 with respect to rates of migration to the Faroes and Iceland, recaptures from the North Sea and northern Norway not given.
c Included in the total recaptures from taggings in northern Norway in 1954-80 given above.
d Only the number of recaptures from Iceland and the Faroe Islands given.
e Part of the recaptures from these experiments included in total recaptures for 1954-80.

Sources: 1) Olsen 1959, 2) Jones and Jónsson 1971, 3) Jakobsen 1978, 4) Jakobsen 1978a, 5) Jakobsen 1978b , 6) Jakobsen 1978c, 7) Jakobsen 1981, 8) Jakobsen and Olsen 1987, 9) Nicolajsen 1995

For the sake of curiosity it is noted that 3 saithe, tagged north of Iceland in 1964 and 1965, were caught off W-Greenland.

The results of the tagging experiments conducted by Norway, concerning migration to Iceland and the Faroes, are dealt with most thoroughly by Jakobsen and Olsen (1987). These authors give recapture rates in Norwegian statistical areas 06 and 07, which encompass the Northeast arctic saithe's main spawning grounds off the central west coast of Norway and compare them to recaptures at the Faroes and at SE- and NW-Iceland, but only from taggings in northern Norway. The return rates are given relative to returns per 1 000 tons fished by German vessels, scaled to represent 1 000 fish tagged each year. Such scaling makes numbers from different periods comparable, although the tagging effort might have varied. Furthermore, the analysis was restricted to returns from the northernmost releases only, *i.e.* some 40 000 out of a total of 87 000 tags (Jakobsen 1995). Since numbers have been scaled we can neither study single tagging experiments with respect to returns by area, nor are there data for all areas. However, recaptures have been made at Iceland from taggings in other areas off Norway (Jakobsen 1978, 1978a, 1978c, 1981, 1995; Bjordal and Skar 1992).

From the Norwegian tagging experiments, which still continue, 106 tags out of 40 000 saithe tagged north of 68°30'N were returned from Iceland, 55 from the Faroes and 388 from Norwegian statistical areas 06 and 07. This, together with the fact that in some years in the period 1954-1980, return rates from one or both of two Icelandic subareas were actually higher than from areas 06 and 07 off the central west coast of Norway, is given as evidence of an ongoing and sometimes large-scale migration to Iceland and the Faroes (Jakobsen and Olsen 1987). That the westward migration may in some years take the form of mass movements has also been suggested previously (Schmidt 1958; Olsen 1959, 1961; Reinsch 1976). The English/Icelandic taggings in 1964 and 1965 and their returns are often cited as indicating that an emigration from the Icelandic area is less likely, *i.e.* that the traffic is one-way (Jones and Jónsson 1971; Jakobsen and Olsen 1987).

It is interesting to apply the same analysis as Jakobsen and Olsen (1987) to the results of Jones and Jónsson (1971), *i.e.* returns from spawning grounds *vs.* returns of emigrant tags, the underlying assumption being that the migrations are spawning migrations. From maps showing the distribution of tag returns around Iceland, the returns from an area encompassing the spawning grounds of the Icelandic saithe were counted. This area was defined as the shelf area south of Iceland, with boundaries along latitude 65°30'N in the west and 64°30'N in the east. This area division is based on the distribution of the two main water masses in the Icelandic shelf area, and is much used when analysing the results of the Icelandic groundfish survey. The counting is given in Table 2.3 and the results of the two analyses are compared:

Table 2.3. Comparable figures from the Norwegian experiments of 1954-1980 and from the English/Icelandic experiment of 1964 and 1965

	Recapture locality		
Tagging locality	Home spawning grounds	Faroes	Other side of the Norwegian Sea
North of Iceland	55 (80%)	8 (11%)	6 (9%)
Northern Norway	388 (71%)	50 (10%)	106 (19%)

Sources: Jones and Jónsson 1971, Jakobsen and Olsen 1987

Obviously, these experiments indicate a similar pattern of recaptures at the home spawning grounds and away from home for both stocks, *i.e.* about equal probabilities for a saithe from Iceland migrating to Norway as for the opposite case. This statement is independent of any considerations about fishing mortality, tag density, age at maturity, recapture rate and so on, if emigrant spawners and home spawners are identical until the onset of maturity and the choice of spawning ground is made.

At least two authors (Jakobsen 1995; Nicolajsen 1995) mention return rates having dropped over the years. This leads to speculations on whether return rates may differ according to area, the Icelanders, then, being the most diligent tag returners. Another point, worth attention, is the difference in relative returns taken west of Scotland and from the North Sea from Faroese and English taggings at the Faroes. It seems reasonable to assume that the rate of returns from the area closest to the laboratory that "owned" the tags is highest, since the fishermen close to the release areas are likely to be better aware of the taggings and the importance of returning tags than their collegues in other countries or farther away.

2.2. Deviations in mean length at age

Reinsch (1976) discusses the mobility of the saithe in his monograph on this Atlantic species. He quotes Schmidt (1958) as having described deviations from a 5 year average MLA in data from German landings of Icelandic saithe. Schmidt's findings show a deviation becoming apparent in catches taken at NW-Iceland in July and August 1957 from the 1949-1951 year classes. Reinsch then demonstrates the same phenomenon for the 1958-1961 year classes in 1965 and for the year classes from 1961-1963 in 1969. As supporting evidence an extraordinary drop in strength of the 1960 year class in Norwegian waters in 1965 is given. Reinsch concludes that migrants from Norway had reached SE-Iceland in April-May and then spread to other fishing localities later in the year. These findings indicate an immigration of saithe to Iceland.

The possibility of an emigration of saithe from Iceland has also been pointed out by previous authors (Schmidt 1957; Reinsch 1976). Apart from referring to Jones and Jónsson (1971), Reinsch (1976) states that the proportions of some year classes in German saithe landings from Iceland and the Faroe Islands show reciprocal variations, namely, that on at least two occasions a strong year class at Iceland has been reduced disproportionately from one year to the next, while it has increased in strength at the Faroes beyond the normal prognosis. The hypothesized emigration from Iceland is taken to occur at a later age than in the case of the immigration of saithe from Norway. In this case, the evidence of numbers in catches from the year classes is the basis for the emigration theory since the growth rates of saithe at Iceland and the Faroes, estimated from samples of German catches, were similar (Reinsch 1976).

2.3. Indications in VPA data

In a report of the North-Western Working Group (NWWG) of ICES three points are made which could support the hypothesis of an immigration of saithe to Icelandic waters in 1991 (Anon. 1992). First, large discrepancies were found between predicted and actual catch at age 7 in 1991 (*i.e.* the 1984 year class) and, second, the observed mean weight for this age group in the catch was lower than that predicted by the model used by the NWWG. In addition, a comparison of the length distributions of age group 7 in 1990 and 1991 shows that the upper halves of these distributions coincide, while the length distribution for age group 7 in 1991 contains markedly higher numbers of small fish, as shown in Figure 2.1. The total number of seven year olds, sampled for age determination in 1991, was more than 50% higher than average, while no such increase was observed for other age groups. However, the abundant 1984 year class was also represented in numbers higher than average already as 5 and 6 year olds in the two previous years, and shows a negative deviation in both mean length and weight for these age groups.

2.4. Larval drift

During a research programme on the distribution of fish eggs and larvae (HELP), conducted by the Institute of Marine Research (IMR), Bergen, off the Norwegian coast in April - May 1985-1992, saithe postlarvae were in some years observed drifting in from spawning areas outside of Norwegian waters (Bjørke and Sætre 1994; Nedreaas and Smedstad 1995). This was probably the case in 1985, when these surveys started, although a clearer picture might have been achieved by beginning the survey earlier in the year as was done in the following years. A westerly distribution was observed in 1986, 1987 and, to some extent, in 1988. An example of this type of distribution is shown in

Figure 2.2, where it is evident that concentrations of postlarvae entered the survey area at approximately 63°N, near the zero meridian. During the remaining years of the programme a more coastal distribution was observed.

The sources of the imported larvae remain an open question, which will be difficult to answer with present state of knowledge. A hypothesis has been put forth stating that the immature saithe in the area off the coast of Norway between 62°N and 66°N originate mainly from spawning grounds other than the known grounds in that area. These spawning grounds are, ranked in order of importance, the North Sea, Iceland and the Faroes (Bjørke and Sætre 1994).

3. Methods used for estimating a migration

Long distance migrations of fish are mainly connected with spawning or feeding. The means by which the fish find their way across the oceans remain something of a mystery, especially in the case of homing. A whole suite of signals has been mentioned as possible explanations for the orienting capabilities of fish. Some combination of these, along with an element of randomness, must be regarded as the most likely mechanism (Harden-Jones 1968; Legget 1977). This fascinating topic will not be dealt with here but some of the methods used to account for migration in virtual population analyses by assuming that migration takes place, either continously or as isolated events, will be described.

The Northeast arctic and North Sea saithe stocks have been assessed by VPA with the inclusion of a migration from an area north of 62°N south to the North Sea. Jakobsen (1981a) effectively redefines the boundaries between these two stock units. All juveniles (age groups 1-4) in an area off the coast of Norway between 62°N and 64°N are assumed to end up in the North Sea, while the older fish in this area belong to the Northeast arctic saithe. The landings from this area were then divided accordingly in separate VPAs for the two stocks.

The ICES Coalfish Working Group (Anon. 1983) tried a different approach. Juvenile Northeast arctic saithe found in an area between 62°N and 66°N were considered potential migrants to the North Sea and the proportion migrating annually was estimated from tag returns. An estimated rate of emigration was then included in a VPA for the Northeast arctic saithe, and furthermore an equal rate of immigration to the North Sea saithe was assumed. These methods have some obvious drawbacks. The Coalfish Working Group concluded that Jakobsen's procedure overestimated the migration. The use of tag returns to estimate migration rates is questionable due to the non-random distribution of tags in the saithe population (*e.g.* Olsen 1959). A joint VPA for the NE-Atlantic saithe stocks has also been tried and a VPA for saithe in the North Sea and west of Scotland (Anon. 1974; Hastie *et al.* 1995). The conclusion from the joint VPAs has been that the largest stock units tend to dominate the results.

Several alternative models have been proposed for the assesment of immigration of cod from Greenland to the Icelandic cod stock. A summary of four different methods is given below.

1. Shifts in the maxima of catch at age for a year class to ages greater than "normal", coupled with low fishing mortalities (F) at age for the younger age groups from an ordinary VPA, are used to identify migrating year classes (cf. Section 5.4). The Fs for these age groups are then raised subjectively to a level similar to that for the adjoining year classes, or, in the case of consecutive year classes showing evidence of migration, to fit a likely fishing pattern. The migrating quantities are estimated by running the VPA again, but now with the manually adjusted Fs. The estimate of the number of migrants is the numbers of cod one needs to add to the VPA to solve the equations. This method has been applied to the Icelandic cod data for hindcasting immigration from Greenland back to 1941 (Schopka 1993).

2. In the assessment of the Icelandic cod stock, an ADAPT type of tuned cohort analysis (Gavaris 1988; Stefánsson 1988), which incorporates an estimate of migration, is used. For years and ages, at which migrations are known to have occured, a parameter representing migration is added to the model. The results of the cohort analysis for a given set of terminal Fs and, in our case, of numbers of migrants, are tuned to catch per unit effort (CPUE) data from a number of fleets, *i.e.* CPUE from different gear types, areas and seasons, including both commercial and survey data. Tuning consists of the minimization of the weighted sum of the squared difference between observed and predicted CPUE, with the prediction based on a simple linear model relating log-CPUE to log-abundance. In the minimization process, the fleets are weighted subjectivly in a manner preventing any single fleet or age group from becoming overly important in the estimation. Migrations are assumed to occur as fixed numbers, estimated by the minimization procedure, as additions to the population at the beginning of a year. The method has been decribed as not very stable statistically and the choice of weights is crucial (Stefánsson 1992; Shepherd and Pope 1993).

3. To overcome the subjectivity of the two previous methods, Shepherd and Pope (1993) propose two different ways to model migration. One of these is a VPA conducted on a restricted age range, considered free of any contamination by migrating fish. For the Icelandic cod, ages 6 and younger were included in the analysis on the assumption that migrants have generally reached age 7. An extended survivors analysis (XSA) is performed with different restraints on terminal Fs and a weighted average of the resulting Fs is used in the final model. Migration is estimated, in numbers of 3 year-olds, as the difference between the recruitment estimates from conventional VPA and the XSA on the restricted age range.

4. In the same paper, a simple method for estimating a migration is proposed. These authors take large negative residuals from an ANOVA, attempting to explain the logarithm

of the weight at age in the catches in terms of age, year and year class effects, coupled with a high ratio between year class strengths at Greenland and Iceland, as an indication of a migration. The proportions in which residents and immigrants from these yearclasses mix, as 6-8 year old fish, are estimated on the basis of differences in mean weights. The mean weight at age of immigrants from Greenland is obtained from data on their source population. For the residents at Iceland, a crude estimate of mean weight is found by performing an ANOVA similar to the one just described, but excluding from the ANOVA the candidate year classes after they reach the likely age of migration.

The last mentioned method will be used here for the 1984 saithe year class at Iceland, but calculations will be based on lengths rather than weights. It is assumed that a migration occurred in 1991 but, instead of using a mean length estimate for the resident part of the year class from a predictive ANOVA, a set of four mean lengths of age group 7 will be used, *i.e.* 77, 78, 79 and 80 cm. However, performing this type of ANOVA on mean lengths for saithe of ages 3-7 in 1985-94, with zero weight given to seven year olds in 1991, predicts a mean length at age 7 in 1991 of 77.5 cm. This indicates that the lower two of the four values selected are the most realistic.

4. Material and methods

4.1. Biological material

The age-length database for Icelandic saithe at the MRI and some summary data on Northeast arctic saithe from the IMR form the main data basis for this study. For our purposes, the material, for both stocks, can be divided in two, according to how it was collected, *i.e.* in a survey or from commercial catches. In the following, different subsets of the Icelandic age-length combinations, will be considered and compared to the appropriate Norwegian data.

The age readings of some 8027 saithe, collected in the Icelandic groundfish surveys (IGFS) which have been conducted in March annually since 1985, form the basis for the calculation of deviations in MLAs from the long term average MLA of all survey data from 1985 through 1992. The IGFS is a systematic stratified survey, used in the assessment of the main demersal fish stocks at Iceland (Pálsson *et al.* 1989). Age readings from other months and vessels were omitted in order to achieve standardization, *i.e.* with regard to season and selectivity of the fishing gear.

For the present purposes, the survey data were insufficient and, therefore, the material was extended to include also samples from commercial catches. All age-length information on the saithe year classes since 1959 was extracted from the fish data base at the MRI. These data were screened graphically and obvious outliers omitted, *i.e.* the points, lying clearly isolated outside the main range of the data, were deleted. The age-length combinations from this analysis are shown in Figure 4.1. Data were limited or missing for some years early in the period. Since 1974 sampling has been continous and in fair numbers for most years and year classes and that period was, therefore, chosen as the basis for further analysis.

The age was determined from broken sagittal otoliths by trained staff at the MRI. Although no validation study of these age determinations has been undertaken, saithe otoliths are generally considered easily read (Anon. 1995c) in agreement with the consensus on its relative, the cod (Jørgensen 1992).

For Northeast arctic saithe, two sets of mean length data were made available (K. Nedreaas, IMR, pers. comm.). The first gives the mean length at age from four autumn surveys, *i.e.* in 1988, 1989, 1993 and 1994, based a total of 2 880 fish. The surveys covered an area off the Norwegian coast, extending from Møre into the western part of the Barents Sea. In addition, mean lengths at age in samples from commercial catches for the period 1984-1993 were used.

Recent reports of the Arctic Fisheries Working Group and the NWWG of ICES were used as sources of relevant VPA statistics for the two stocks, *i.e.* catch at age, mean weights at age, and fishing mortalities for each age group over the years (Anon. 1993, 1995, 1995b).

4.2. VBGF model specification

Von Bertalanffy's growth function (VBGF), for describing the relationship between age and length, was used as a tool for comparing the growth of Icelandic and Northeast arctic saithe. The likelihood ratio test procedure described by Kimura (1980) was followed. VBGF was fitted to mean lengths at age of pseudocohorts, obtained by pooling data from 4 autumn surveys off the coast of Norway (1988, 1989, 1993 and 1994) and from 8 consecutive IGFS surveys in spring (1985-1992). Mean length at age was modelled by:

$$\bar{l}_{ij} = l_{\infty_i}\left(1 - \mathrm{e}^{-K_i\left(t_{ij}-t_{0_i}\right)}\right) + \varepsilon_{ij} \qquad (4.1)$$

where i denotes stock and j age group; t is the age, adjusted for the half year difference in timing of surveys; l_∞ is the asymptotic length; K is the parameter generally dubbed the growth parameter; t_0 the hypothetical age at length zero; and ε_{ij} is an error term, assumed independent and normally distributed. In order to test hypotheses concerning model parameters, model (1), which allows separate parameters for the two stocks, was compared to constrained versions of the model, *i.e.*:

$$\bar{l}_{ij} = l_{\infty}\left(1 - \mathrm{e}^{-K\left(t_{ij}-t_{0}\right)}\right) + \varepsilon_{ij} \qquad (4.2)$$

with l_∞ , K and t_0 common for the two stocks corresponding to a null hypothesis of complete parameter equality;

$$\bar{l}_{ij} = l_{\infty}\left(1 - \mathrm{e}^{-K_i\left(t_{ij}-t_{0_i}\right)}\right) + \varepsilon_{ij} \qquad (4.3)$$

a model with a common asymptotical length when the null hypothesis is: l_∞ is equal for the two stocks;

$$\bar{l}_{ij} = l_{\infty_i}\left(1 - \mathrm{e}^{-K\left(t_{ij}-t_{0_i}\right)}\right) + \varepsilon_{ij} \qquad (4.4)$$

where the growth parameter is constrained and the null hypothesis: K is the same for both stocks; and finally

$$\bar{l}_{ij} = l_{\infty_i}\left(1 - \mathrm{e}^{-K_i\left(t_{ij}-t_0\right)}\right) + \varepsilon_{ij} \qquad (4.5)$$

when the hypothetical age at length zero is assumed the same for both stocks, corresponding to H_0: t_0 is common for Icelandic and Northeast arctic saithe.

These hypotheses were then tested by comparing the residual sum of squares from the full model (1) to that of one of the constrained models (2-5) by calculating the test statistic

$$-N\ln\left(\frac{\hat{\sigma}^2_\Omega}{\hat{\sigma}^2_\omega}\right) \qquad (4.6)$$

where N is the total number of observations from the two stocks; $\hat{\sigma}^2$ is the mean residual sum of squares from a model fit; Ω and ω denote the full model and one of the constrained models, respectively. This test statistic will under H_0 have an asymptotically χ^2-distribution with degrees of freedom equal to the number of parameters fixed (Kimura 1980).

4.3. Mixture model

In order to estimate the magnitude of the hypothesized migration of pre-spawners or first-time spawners from Norway to Iceland, the following assumptions were made. A given age group was treated as a mixture of two components, one resident at Iceland assumed to experience "typical" growth and the other of immigrants from Norway assumed to have a mean length close to that observed in the Norwegian landings of that age group. We then proceed to use the "mixture model" to obtain a rough estimate of the proportions of the components constituting the mixed population (James 1978; Shepherd and Pope 1993; cf. Appendix).

In our hypothetical example, four values were chosen of a mean length for the resident component, since there is no way of pinpointing that parameter as of today. The values chosen were 77, 78, 79 and 80 cm, all well within the observed range of mean lengths for age group 7 at Iceland. The mean length of the immigrants was kept fixed at 69 cm, which is close to the value observed in the Norwegian data. The mean of the mixed distribution is set at 76 cm, *i.e.* close to the mean length of age group 7 in Icelandic samples in 1991. Estimates of the mixing proportion are calculated from the model using a sample size of 1 500, *i.e.* close to the actual numbers sampled from age group 7 in 1991.

Given this set of assumptions we proceed to estimate the proportion of immigrants in the mixture by the formula:

$$\tilde{p} = \frac{\overline{X} - \mu_2}{\mu_1 - \mu_2} \tag{4.7}$$

and obtain an approximation of the precision of that estimate using a plug-in-estimate for the variance:

$$Var(\tilde{p}) = \frac{Var(\overline{X})}{(\mu_1 - \mu_2)^2} \tag{4.8}$$

where $\tilde{p}$ is the moment estimate of the mixing proportion, $\overline{X}$ is the observed sample mean of the mixture, n the sample size, and μ_1 and μ_2 are the means of the two components (James 1978; cf. Appendix).

4.4. Simulation

To investigate the performance of the approximation of the variance of the mixing proportion, mixing in given proportions was simulated by sampling from two normal distributions, one of residents, and the other of the generally smaller immigrants, under two different model assumptions about the mixing of components.

To study the precision of the estimate of the mixing proportion some assumptions about the varibility of the components have to be made. A coefficient of variation (CV) of 10% for both component distributions is assumed, *i.e.* that the standard deviation is 6.9 cm for the immigrants and somewhat larger for the residents. This value is based on an examination of the data on 7 year olds from both areas. In the Norwegian samples from all of the years 1984-1993, 99% of the observations of the length of age group 7 were contained within a range of 30 cm or less. If lengths are normally distributed, that range should, according to normal theory, have a width of approximately 5 standard deviations. For the Icelandic saithe the coefficient of variation in length from all age-length couples for 7 year olds, since the mid-1960s, was in the range of 5-9% in all years, except 1991, and incidentally also in 1983 for the 1976 year class, when it exceeded 11% (see Appendix Table IV).

Model 1

Components were assumed to be completely mixed and sample size considerations did not enter the model other than the total number of fish was kept fixed at 1 500.

Model 2

Components were assumed to be totally separated in the mixture, with probabilities p and 1-p of a given subsample coming from the immigrant and resident components respectively. When it had been decided from which component to sample, a sample size was drawn at random from a vector of the sizes of samples actually taken from 7 year-olds in 1991, the distribution of sample sizes shown in Figure 4.1. It is, in other words, assumed that residents and immigrants occur separately in similar sized schools. Sampling was continued until the total sample size had reached 1 500 in the first run. In later runs sample size was increased until the same nominal precision, as in the simple complete mixing model, had been achieved.

Component means and numbers sampled were the same as described for age group 7 in 1991 in section 4.3. Proportions simulated were the appropriate estimates from the application of the mixture model. The number of simulations was 10 000 for the first run of both models but in later runs of model 2 the number of simulations was reduced to 2 000. In the simulations components were sampled in propotions from James's formulas, given to an accuracy of 3 decimals.

5. Results

5.1. Growth difference

The standard VPA tables, giving mean weights at age in the catch, were used as data sources to illustrate the growth difference between the two stocks. Figure 5.1 shows growth in terms of annual weight increment as a function of mean weight. Another view of these same data is shown in Figure 5.2 where the mean weight of selected year classes is plotted as a function of age. Here the VPA mean weights at age for the Norwegian saithe are shown to be separated from those of the Icelandic saithe. The figures clearly show a growth difference between the Northeast arctic and the Icelandic saithe. Figure 5.1 further shows the intermediate nature of the Faroe saithe.

Figure 5.3 shows survey MLA's for Icelandic and Northeast arctic saithe together on the same plot, with ages shifted to account for the approximately half year difference in timing of the surveys. Von Bertalanffy's growth function was fitted to these survey mean length data. The model fit showed a difference between the two stocks both for the growth parameter, K, and the asymptotic length, l_∞ (likelihood ratio test, $p<0.01$). A further analysis should perhaps be performed by year classes on data sets of individuals from both/all stocks within a modelling framework, including a larger set of explanatory variables, *e.g.* food availability, stock size and temperature.

5.2. Variability in the size at age data

Deviations in mean length and weight at age from the average for Icelandic saithe are shown in Figure 5.4. The length deviations are derived from IGFS data during 1985-1992, while deviations in weight at age are based on samples from the commercial catch in 1979-1993. For the most part, there is a correlation between the deviations in length and weight. Of particular interest are the year classes of 1976 and 1984 which, due to their large negative deviations, can be followed over several years.

MLAs were calculated on a quarterly basis for saithe sampled from trawl catches in two different areas, with a east-west division along 18°W. The reason for this division is, simply, that an immigration from the east is bound to appear first on the fishing grounds off the eastern part of Iceland. Samples from trawl catches were chosen since they generally yielded the highest number of saithe, were spread fairly evenly in space and time and because the trawl is less selective than the gillnet, the other main fishing gear.

The results are shown in Figure 5.5, where changes in mean length of the year classes 1981-1986 can be followed. It is clear that the the saithe in the eastern area tend to be smaller, but no clear indication of the arrival of immigrants is apparent. The same data, plotted on a monthly basis, did not yield any additional information.

Means, numbers sampled, standard deviations and coefficients of variation of the length distributions from saithe age groups 4-10 for the year classes since 1970 are given in Appendix Tables I-IV. The standard deviations for the year classes 1976 and 1984 were not markedly higher than average for age groups 4 and 5. For age groups 6 and older, on the other hand, they were among the highest on record. This added variability after the age of 6, coupled with the low MLAs for these year classes, is also apparent in the table of CVs. Contrary to the trend for most other year classes, these two show an increase in CV for ages 6 and 7.

It is possible to explain the negative deviations in size over a number of year by shortage of food, *i.e.* intra-specific competion or density dependence. On the other hand, increased variability in lengths after a certain age would not be expected as a result of general food shortage and is more reasonably explained by an immigration. However, it should be borne in mind that the variability of a length distribution is sensitive to other factors, such as numbers sampled from each gear type.

5.3. Catches and Fs at age

From the available VPA data on the year classes of 1962 through 1987 it is observed that catch at age generally peaks at age 6, for a few year classes at ages 4 and 5. Exceptions are the 1962, 1964 and 1984 year classes which are represented in greatest numbers in the catches as 7 year old fish in 1969, 1971 and 1991. The 1984 yearclass was also numerous in 1990 , with over 10 million fish caught during that year also. The 1976 year class shows a secondary peak in the catches at age as 10 year old fish in 1986. Catches at age from year classes of saithe at Iceland since 1962 are shown in Figure 5.6.

Tables of Fs at age were also scrutinized for Schopka's indication of a migration, *i.e.* a drop in F in years and at ages prior to a migration event. The Fs at ages 5 and 6 were also among the lowest on record for both the 1977 and 1984 year classes. In addition F at age 9 for the 1977 yearclass in 1985 is given as 0.213 which is far below the average for 9 year-olds. Fs were only examined as far back as to 1970, thereby omitting the not as recent 1962 and 1964 year classes, since less confidence must be attached to the the results of a historical VPA than for the past two and a half decades.

Table 5.1. Estimates of the mixing proportion (prop.) and its standard error (s.e.) from mixture model and simulation results. Mixture model estimates based on a mixture mean of 76 cm. Immigrant mean 69 cm and CV 10% for both components in all cases. **Model 1** simulates complete mixing of components, **Model 2** components separate within mixture. **n** denotes sample size, **S** number of simulations. For Model 2 sample sizes are at least **n**, depending on how sample sizes were drawn.

		Simulation setup		Resident mean			
		n	S	77	78	79	80
Mixture							
model	prop.	1 500		0.1250	0.2222	0.3000	0.3636
estimates	s.e.			0.02599	0.02433	0.02294	0.02177
Model 1	prop.	1 500	10 000	0.1249	0.2218	0.3002	0.3639
	s.e.			0.02602	0.02388	0.02301	0.02158
Model 2	prop.	1 500	10 000	0.1236	0.2219	0.2996	0.3638
	s.e.			0.05674	0.06840	0.07548	0.07845
Model 2	prop.	5 000	2 000	0.1253	0.2221	0.2985	0.3631
	s.e.			0.03221	0.03815	0.04069	0.04286
Model 2	prop.	7 000	2 000	0.1249	0.2223	0.3001	0.3636
	s.e.			0.02624	0.03244	0.03414	0.03584
Model 2	prop.	10 000	2 000	0.1243	0.02210	0.2999	0.3636
	s.e.			0.02180	0.02697	0.02900	0.03056

5.4. Model and simulation results

The uncertainty, associated with the estimation of the mean in a mixed distribution, is negligible for sample sizes close to 1 500, the number of 7 year old saithe aged at Iceland in 1991. On the other hand, the variance of the moment estimate of the mixing proportion is considerable, giving a standard error close to 0.025 for all resident means combined with an immigrant mean of 69 cm. Assuming that, at the sample sizes (≈1 500 fish) under consideration, the mean has been accurately determined, and using the rough normal approximation of doubling the standard error, indicates a 95% confidence interval of ±5% for the estimate of the mixing proportion of the components forming the mixed distribution.

Table 5.1 summarizes the values resulting from the application of the mixture model as well as the results of simulations.

From the results of the simulations we observe that the approximate variance formula and the variance from the simulations are in agreement when complete mixing of the two components is assumed. On the other hand, it is clear that if the components are clumped within the mixture, the variation in the estimate of the mixing proportion becomes much larger. The variance of the sample sizes used will determine how large this increase is. In model 2, the variance of the mixing proportion increases as the proportions of the components approch 0.5, the reverse of what is the case in model 1. Thus, given nearly equal proportions in model 2, there is greater probability of a series of samples coming from the same component, thereby offsetting the estimate of the mixing proportion and increasing the variance.

Increasing the numbers sampled in Model 2 gives an indication of how great the sampling effort must be to approach a standard error of 0.025 for the mixing proportion. Some 7 000 saithe sampled would be required with a mixing proportion close to 0.1, at least 10 000 for proportions close to 0.2, and even more as proportions approach 0.5, for this one age group only. The standard error of the simulated proportions decreases as the inverse of the square root of the sample size, as given by elementary statistics.

6. Discussion

It is evident from previous work on the saithe that the species undertakes trans-Atlantic migrations. These migrations are at times of such magnitude that they result in boom or bust in the cathces from the migrating year classes at different fishing grounds in the area (Schmidt 1957, 1958; Olsen 1961; Reinch 1976; Jakobsen and Olsen 1987). Reinsch gives an example of a record long distance migration of a saithe. On the January 23 of 1958 a saithe was tagged off the south coast of Iceland onboard a German research vessel. Some 55 days later, on March 21, this saithe was caught in the Barents Sea off the Nordkyn peninsula. The shortest distance between the release and recapture localities is more than 1 300 nautical miles, *i.e.* the fish had kept a minimum cruising speed of 24 nautical miles per day. These observations, together with evidence from catch data, have led to our effort to describe the underlying evidence and at quantifying one such migration event.

The results of the tagging experiments on NE-Atlantic saithe show that the local stocks are variously connected and, in the present context, that the Icelandic, Faroese and Northeast arctic saithe intermix. A more balanced distribution of tagging effort among areas seems desirable and a more detailed analysis of the returns from the almost 100 000 saithe tagged at Norway would, undoubtedly, give a more solid basis for understanding these migrations.

The previously held view, that the migration of saithe between Norway and Iceland is mainly one-way should be reconsidered. A new analysis of the results given by Jones and Jónsson (1971), as recaptures from spawning grounds, indicates that a migration in the opposite direction is no less likely. The German anlysis of saithe data together with Faroese tag results also indicates a frequent interchange of saithe along the Faroe-Iceland Ridge.

During the last three and a half decades, irregularities in catch in numbers figures from VPA for Icelandic saithe indicate 3 or 4 cases of immigration. Two of these are further supported by deviations in both mean lengths and weights at age. The VPA figures are naturally nothing more than derivatives of the catch statistics and age-length measurements undertaken through the years and their value will, inevitably, rely on good groundwork. Our study uses two sets of VPA data that have been collected by the same two fisheries laboratories throughout the period, and should therefore be consistent and comparable.

Fishing pattern is obviously one of the determinants of all estimates of mean length at age in the catch. Since the fleet seeks out the best concentrations, it is possible that in response to incoming saithe from Norway, these become overrepresented in the catches thereby biasing mean weights and lengths downward.

The observed irregularities in lengths at age for the strong saithe year classes of 1977 and 1984 at Iceland lead to at least two explanatory hypotheses, *i.e.* density dependent growth and immigration of slower growing saithe. The largest deviations in the MLAs were observed for 9 year old saithe in 1985 and a slightly smaller deviation for 7 year olds in 1991, from the strong 1977 and 1984 year classes, respectively. As stated previously, these year classes also showed a negative deviation from the average in both mean weight and length for the younger age groups . Whether this is an indication of density dependent growth (Olsen 1966), or the result of the immigration being spread over more than one year, is difficult to find out for sure. Furthermore, these two explanations are by no means incompatible, the recruitment to a year class can be a success in more than one saithe stock in the NE-Atlantic in a given year (Jakobsson 1992), this year class can then go on to suffer from density-dependence, and, finally, undertake a trans-Atlantic mass migration, detectable in both source and sink populations (Pulliam 1988).

Observations of saithe fry on the outskirts of the Norwegian fisheries jurisdiction in April and May in some years are not in themselves sufficient to make the case for a hypothesis of larval drift from Iceland, since these fry could easily have drifted from spawning grounds in the North Sea. However, capelin larvae have been observed in the same general area, about two months later in the year. These larvae are beyond doubt of Icelandic origin though some uncertainty is attached to their date of birth (Bjørke and Sætre 1994; H. Vilhjálmsson, MRI, pers. comm.). In view of these two independent observations, a larval drift of saithe from Iceland to Norway and a subsequent migration back to Iceland cannot be ruled out.

In the golden days of the Atlanto-Scandian herring bonaza, saithe were a frequent bycatch in the herring seines and pelagic trawls, with amounts of up to 60 tonnes reported in the latter case (Reinsch 1976). This occured most frequently in the overwintering area east of Iceland and north of the Faroes. Jigging for saithe during breaks from the herring fishery, was a considerable source of income for Icelandic herring fishermen, especially in the late 1960s (H. Vilhjálmsson, MRI, pers. comm.)

Accepting, as we have done here for the sake of argument, that import of Norwegian saithe explains, in part at least, the low mean length and mean weight at age 7 in 1991, the next question is that of numbers? A simple attempt at an answer to this, is to use point estimates of MLA observed for saithe at Iceland and Northeast arctic saithe and some assumptions on growth for a purely resident component, and then apply the mixture model. This yielded an approximate mixing proportion of at least 0.1, probably closer to 0.2, in other words: Some 10-20% of age group 7 saithe in the catches at Iceland in 1991 were of foreign origin, probably Norwegian. If we accept this approximate proportion and the VPA stock in numbers estimate of 35 million 7 year olds in 1991, this immigration would amount to some 3.5 - 7 million saithe or, at a mean weight of 3.5 - 4 kg, a biomass of 12 to 25 thousand tonnes.

It is stressed that, due to the nature of the data, these estimates are only tentative. On the other hand, it is felt that the available evidence lends fairly strong support to a hypothesis of an occasional large scale migration. It is hoped that further studies using the mixture model, will pave the way for dealing more effectively with any future immigration of either saithe or cod to Icelandic waters.

All of this is speculative and the assumptions need further qualifications. A key question is whether the Icelandic and Northeast arctic saithe throughout a year can be regarded as coming from the same length distribution. The main flaw in the argumentation is probably tied to the assumption that observations are derived from the same mixed distribution, when they are, in fact, from distributions that are in no way fixed. The fish grow throughout the year, immigrants arrive at some point, and, although that possibility has not been considered in our analysis, may well leave again later in the year.

Another generalization is the assumption of a constant coefficient of variation of 10%, which is on purpose kept generous. Lowering the CV to 8%, which is closer to what has generally been observed for Icelandic saithe, led to a reduction in the standard errors for the proportion of some 15 - 20%, thus indicating better estimation. The sampling effort needed to obtain a higher precision in the estimation of the mixture proportion by the present method is enormous. Setting the desired precision at 2% or less, would require a sample size of some 10 thousand saithe depending on the component means, their variances and proportions. However, if immigrants arrived early in the year and remained in the population sampled by MRI throughout the year, the mixture model would be an acceptable basis for indicating the numbers of immigrants.

The simulations were carried out in order to examine the accuracy of the approximate variance formula for the mixing proportion given by James (1978). If complete mixing of components is assumed model and simulations agree. However, when components of the distribution remain separate, as would seem likely in the case of separate schools, and, given the sample sizes used here, the accuracy of our estimate of the mixing proportion decreases. A theoretical formula for the variance of the proportion could, no doubt, be derived by also considering the variance of sample sizes. This is left as an exercise for others. The application of the mixture model for the evaluation of migrations is, obviously, dependent on the available data on the fish stocks in question, and the Icelandic saithe are probably lacking in that respect. Anyway, the request by Shepherd and Pope (1993) for further work on the precision of the mixture model has been met to some extent.

Because all age-length couples for 7 year olds at Iceland in 1991 were available, the selection of programs available for the analysis of length distributions might have been applied to our problem (MIX, Multifan etc). However, Sparre (1986, in Kolding and Bergstad 1988) has shown that in order to resolve a length distribution into components, the means must be more than two standard deviations apart no matter what method you use. The other migration assessment methods, described in section 3, might also be used to estimate saithe immigration. Although they have given useful estimates for the cod, the surveying, sampling and assessment of these two species are incomparable.

Using the mixture model as suggested by Sheperd and Pope (1993), with the addition of an approximation of the variance of the mixture propotion, seems more to the point. The presence of normal components is not assumed and there are only two components we need concern ourselves with. In such a case the simple and easily understandable method, although in many ways rudimentary, is preferable in a first attempt at describing these relationships.

If migrating individuals come from the upper part of the length or weight distribution of the source population, the use of the mean lengths or weights of the fish remaining at Norway would lead to an underestimate of the mixing proportion, since it would take a greater number of slightly larger fish to explain a given reduction in either mean length or weight at age. On the other hand, if the energetic stress accompanying the migration is high, the growth of the migrants could be retarded which would tend to counteract this effect.

To further establish and quantify these relations more extensive tagging experiments are needed, in particular on the Icelandic saithe. A combination of morphometric and genetic studies should also be considered. Although the limited number of genetic studies conducted on saithe in the NE-Atlantic to date point towards homogeneity among the stocks, the field of fish population genetics is developing rapidly and the application of new methods could yield valuable insights. Otolith morphometry is also promising. In the case of the Greenland migration to the Icelandic cod some work has been done on differences between resident and immigrant otoliths (Easey 1978), if such a difference is also detectable between the saithe stock units under consideration that could be capitalized on with the state of the art automated age reading apparatus. Also, and perhaps least costly, a more thorough analysis of existing data on saithe might yield valuable insights, *i.e.* following the advice given to ecologists by Frank and Legget (1994).

Schopka (1993) points out that the failure, in the early 1980s, of recognizing the full impact of the return migration of the 1973 cod year class from Greenland, was in part due to optimism connected to the recent extension of the fisheries jurisdiction, and led to an underestimation of the F's in operation and an overestimate of the cod's biomass. This is one of the explanations for the poor state of the Icelandic cod stock at present and demonstrates the importance of developing methods to monitor such mass movements of fish stocks. By studying the dynamics of the saithe stock units in the North Atlantic more closely, we might become better able to prevent them from reaching such dire straits as the Icelandic cod and perhaps learn a lesson or two that could be useful when dealing with other related fish stocks.

Most of the results presented in this paper and the conclusions drawn from them can perhaps be described as **weak inference**, something that students in marine science and fisheries biology, and presumably in other disciplines as well, are warned against and drilled in recognising in the scientific literature. Nevertheless, I would like to make a case for this "scientific method" since we are often not in posession of material that allows the much sought after **Stong Inference** (Platt 1964; Elner and Vadas 1990). Some inference is always better than none as long as it is recognised as such. It seems clear from the findings presented in this paper/study and the review of earlier work that more attention should be given to the wanderings of the North Atlantic saithe.

7. References

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8. Figures

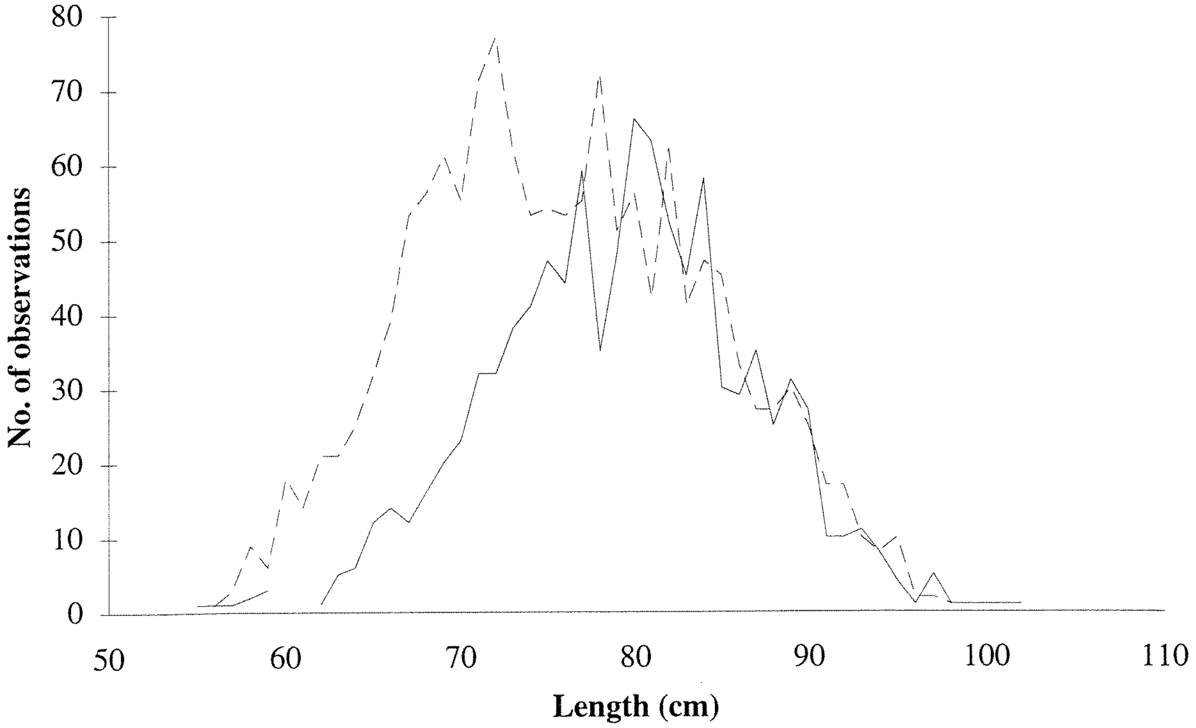


Figure 2.1. Length distributions of saithe age group 7 at Iceland in 1990 (—) and 1991 (---).

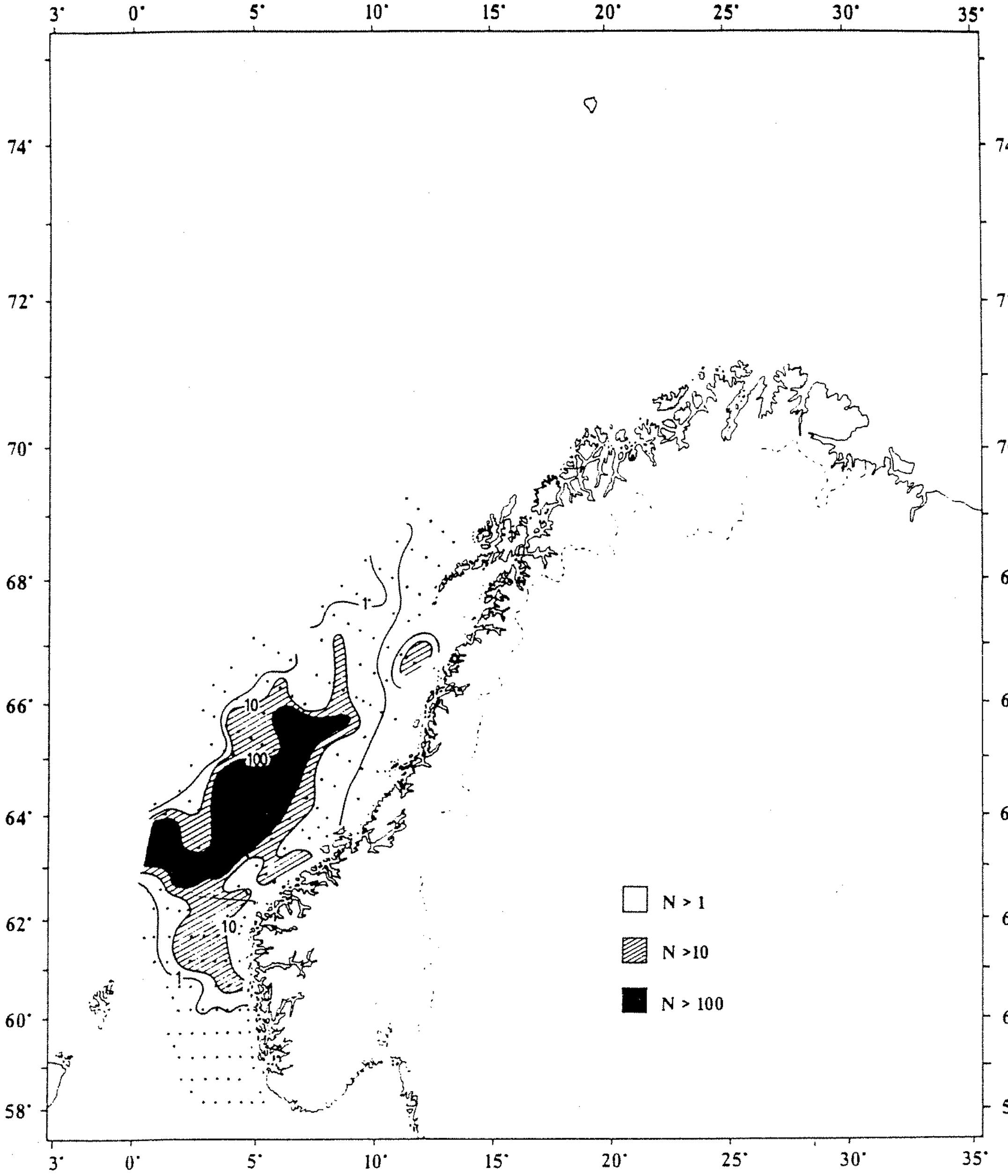


Figure 2.2. Distribution of saithe postlarvae off the west coast of Norway in April-May 1986. The black area represents the highest numbers. Source: Bjørke & Sætre (1994).

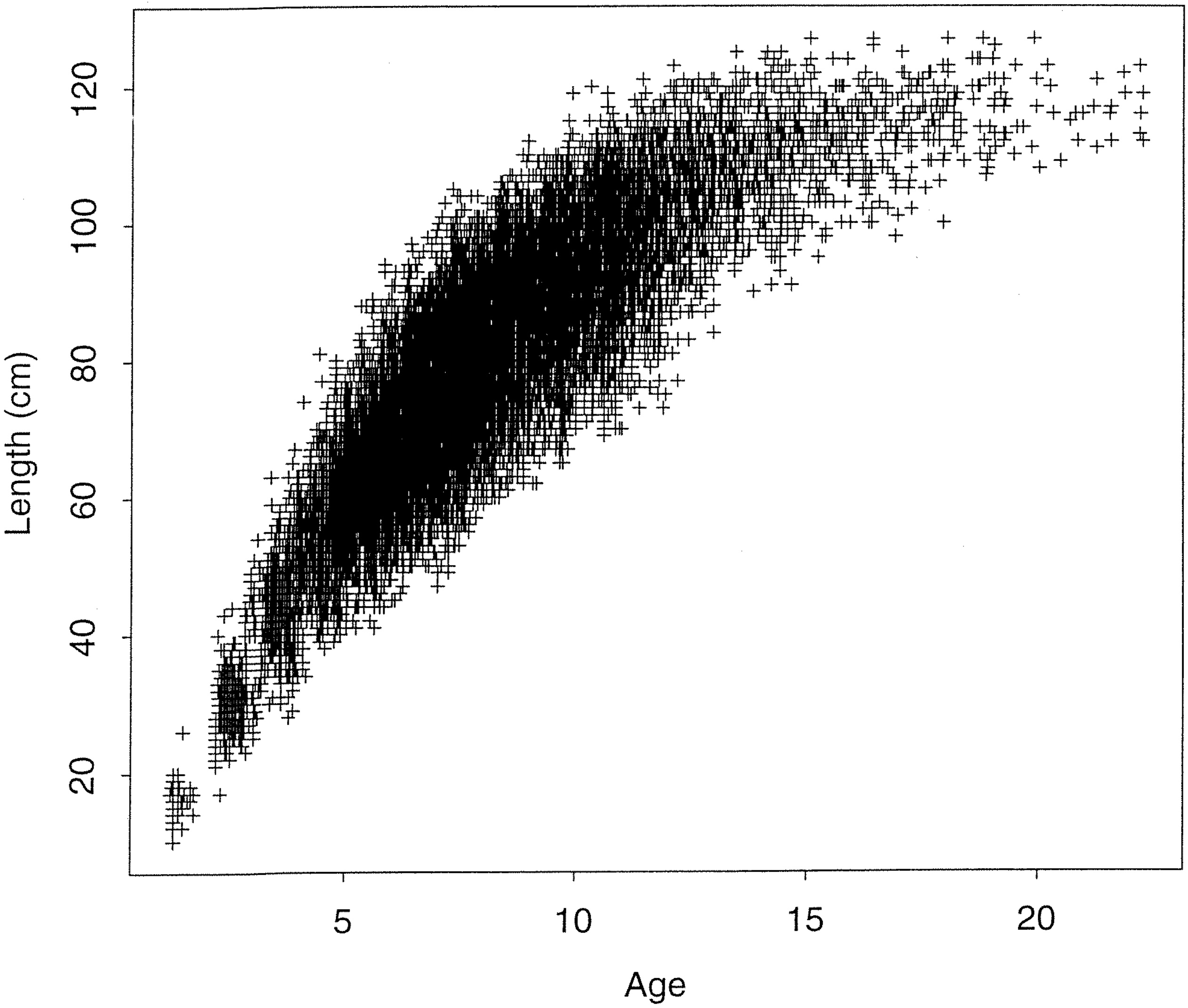


Figure 4.1. Scatterplot of length at age for saithe at Iceland. Year classes since 1962 are included.

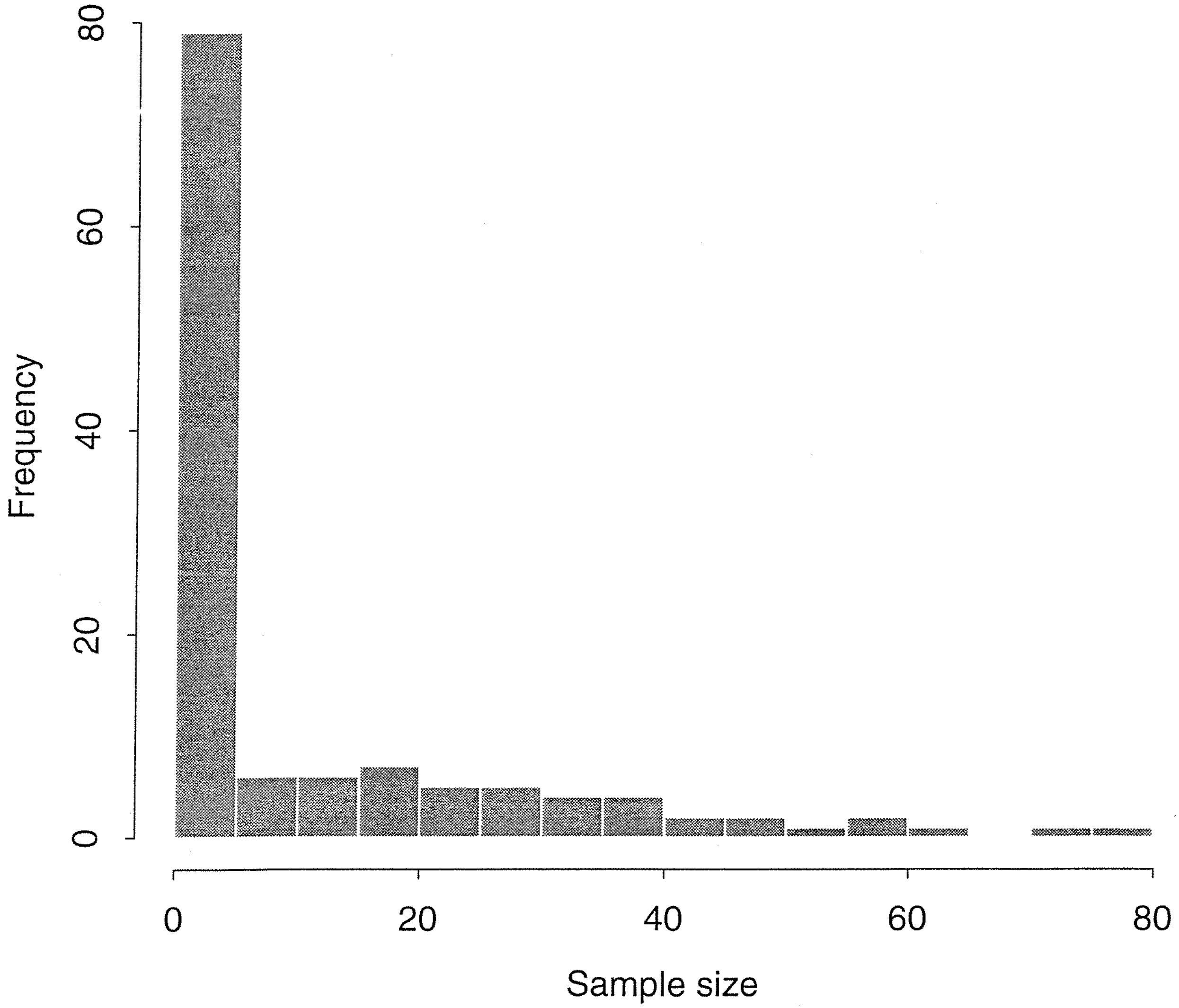


Figure 4.2. Sample sizes of age group 7 in 1991.

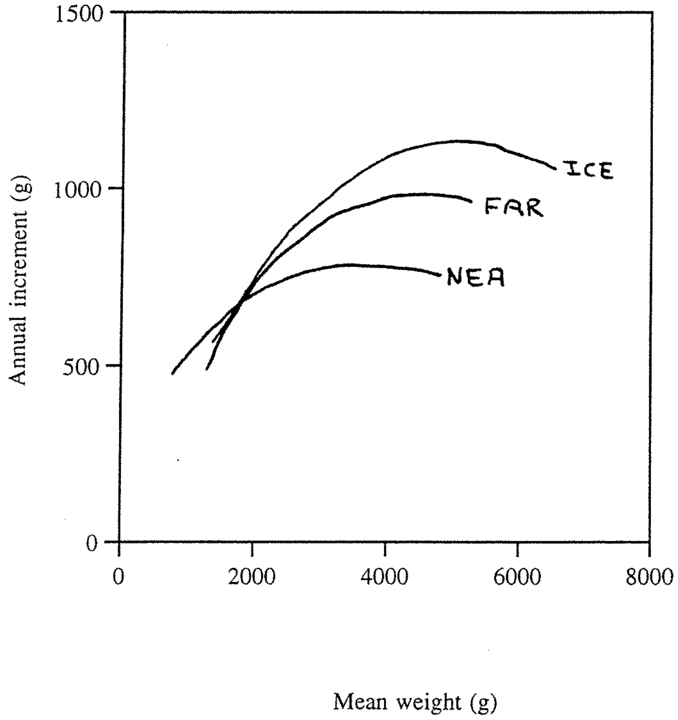


Figure 5.1. Relationship between annual growth increment and mean weight for Icelandic, Faroese and Northeast arctic saithe. Based on average mean weights and their increments for age groups 3-10 in the period 1980-1993. Data from the MRI, the NWWG and the Arctic fisheries WG.

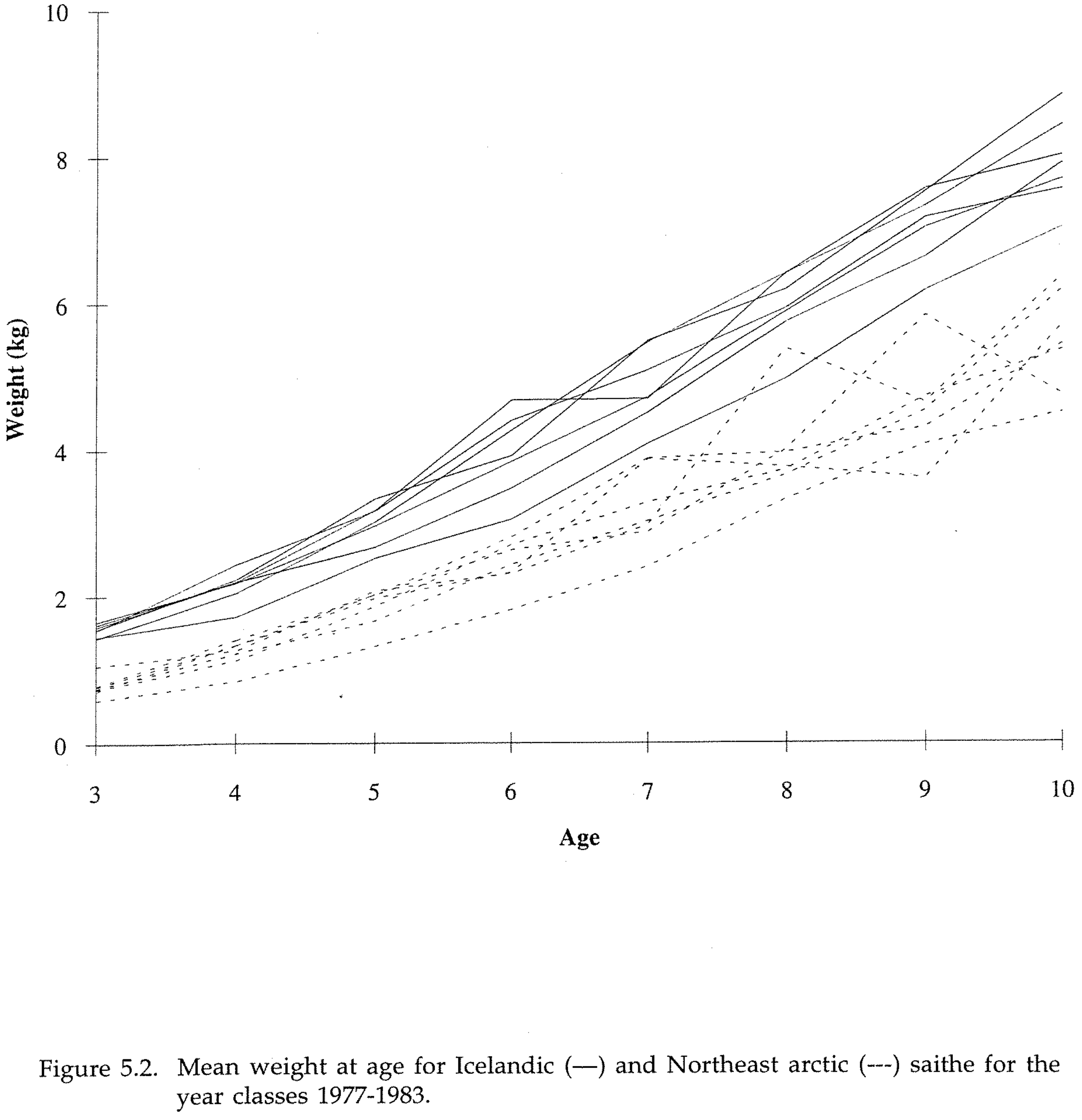


Figure 5.2. Mean weight at age for Icelandic (—) and Northeast arctic (---) saithe for the year classes 1977-1983.

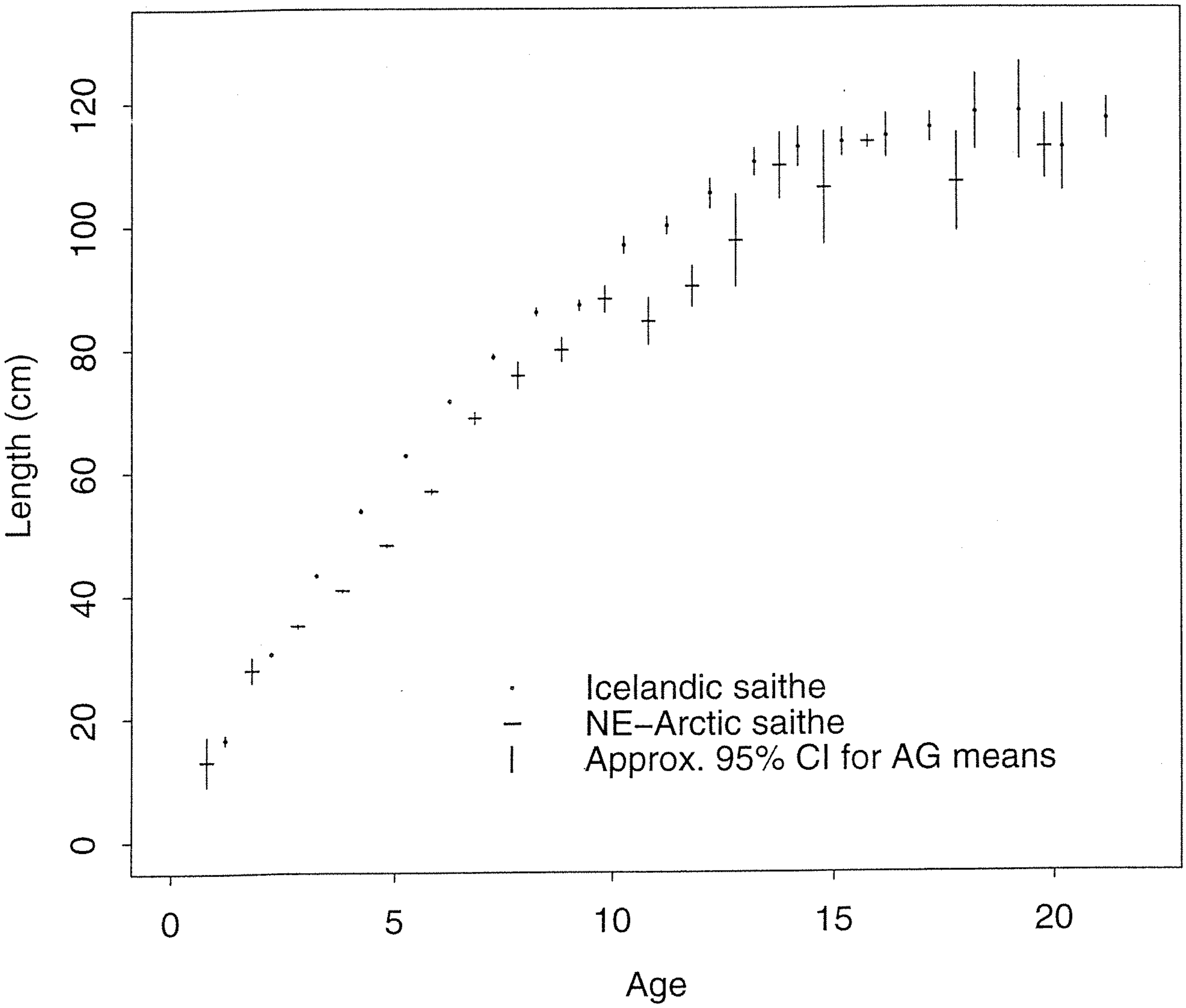


Figure 5.3. Survey MLAs for Icelandic and Northeast arctic saithe. Averaged over 8 and 4 surveys respectively.

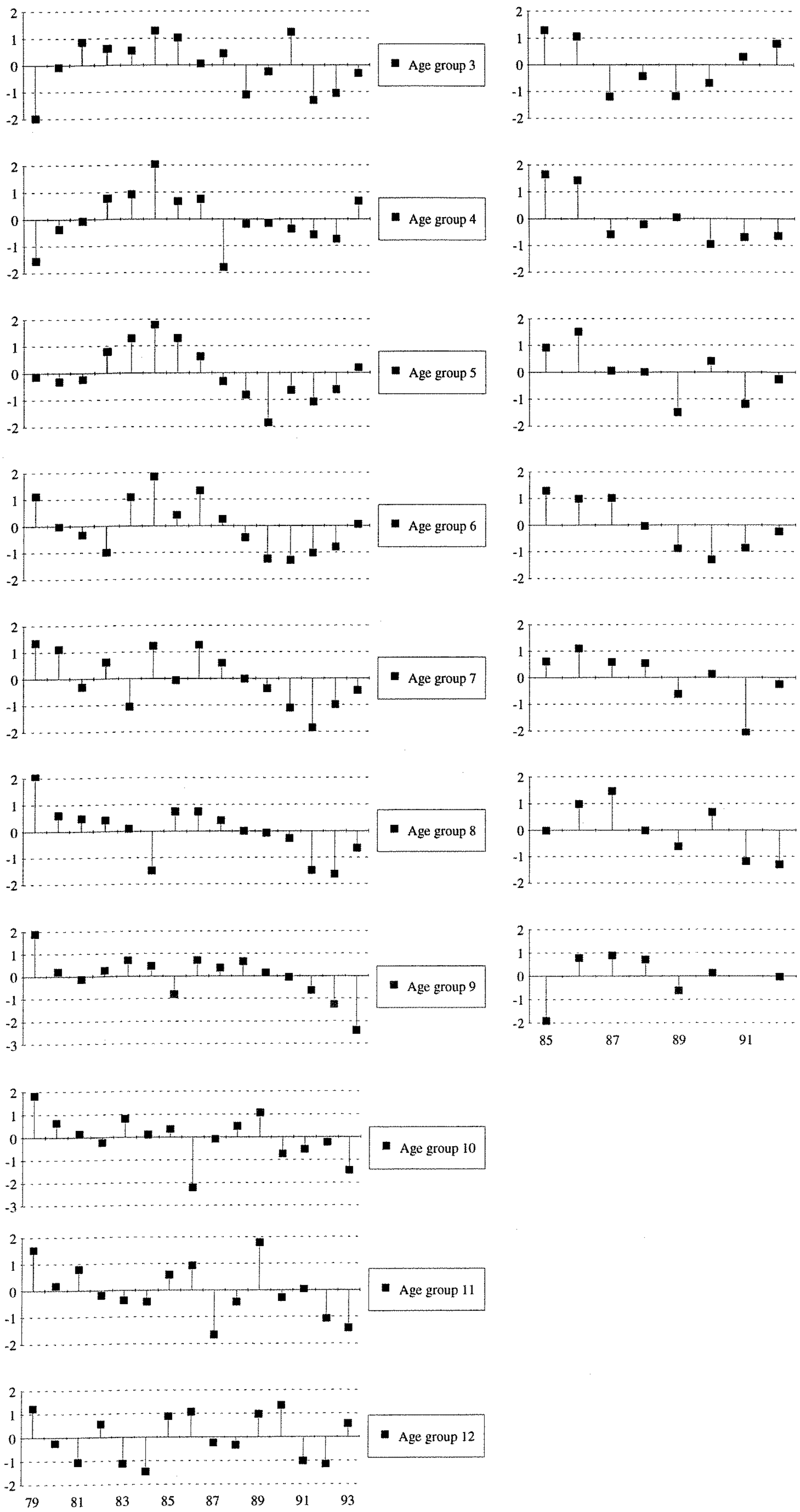


Figure 5.4. Standardized deviations in mean weight and length at age for Icelandic saithe from the average in the period indicated. Deviations in mean weight are based on VPA tables giving mean weight age in the catches, deviations in mean length at age are derived from IGFS data.

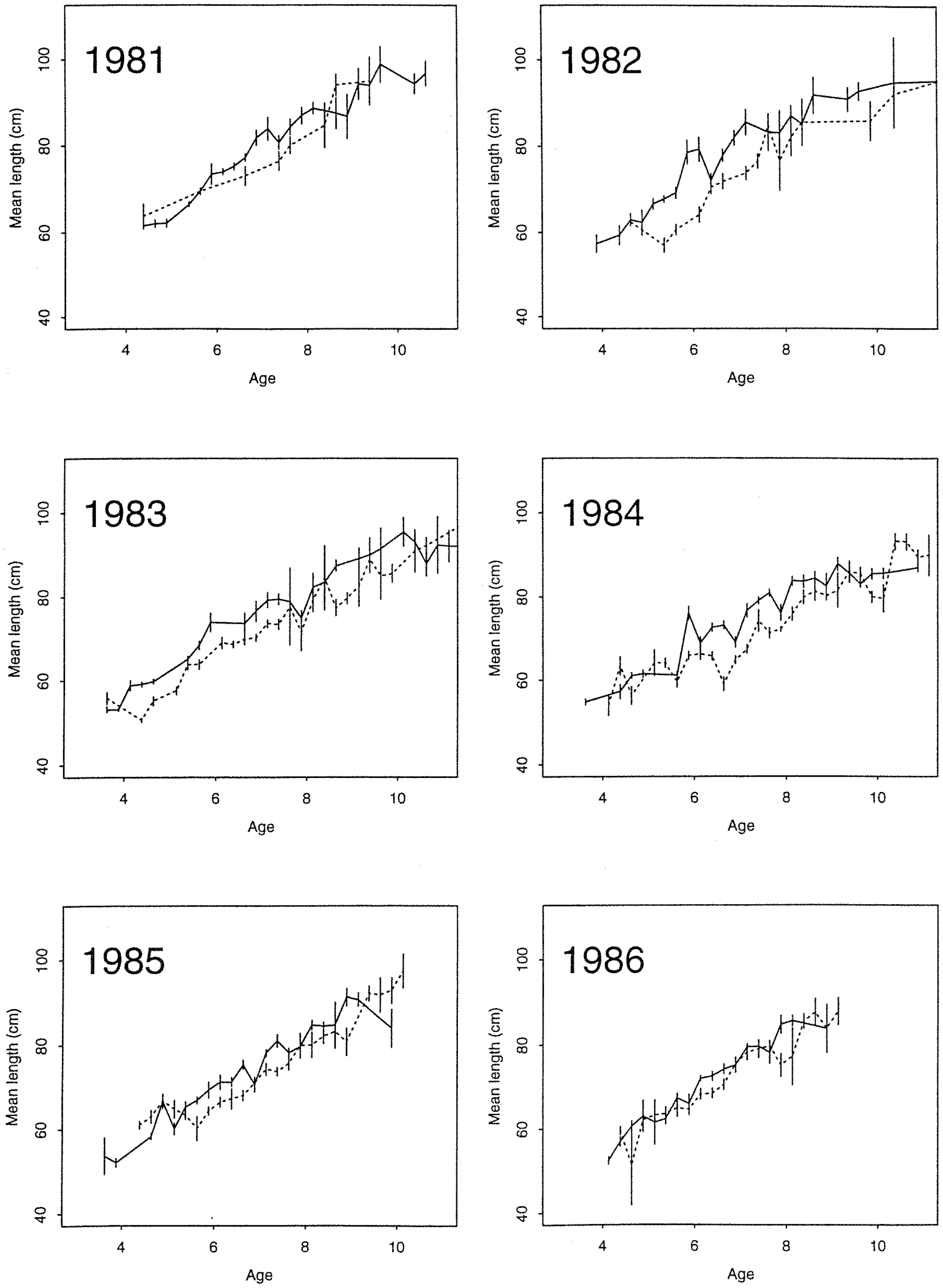


Figure 5.5. Quarterly MLAs for the year classes 1981-1986 west (—) and east (---) of 18°W. Approximate 95% confidence intervals based on the t-distribution are indicated.

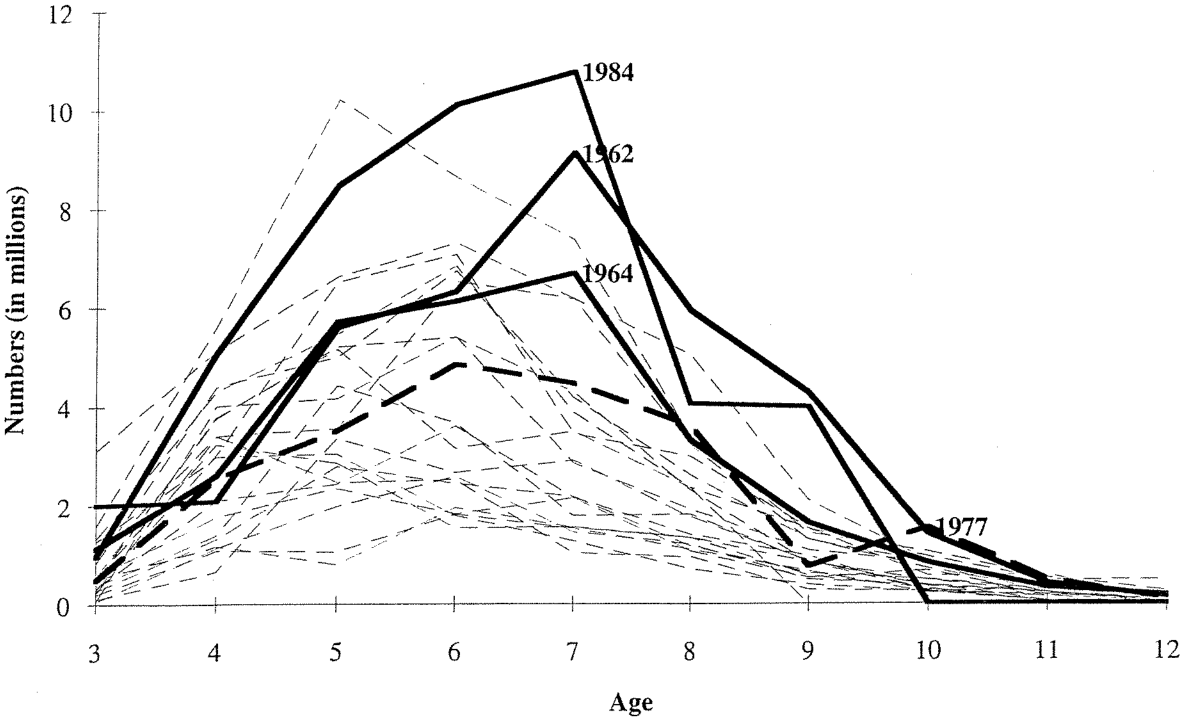
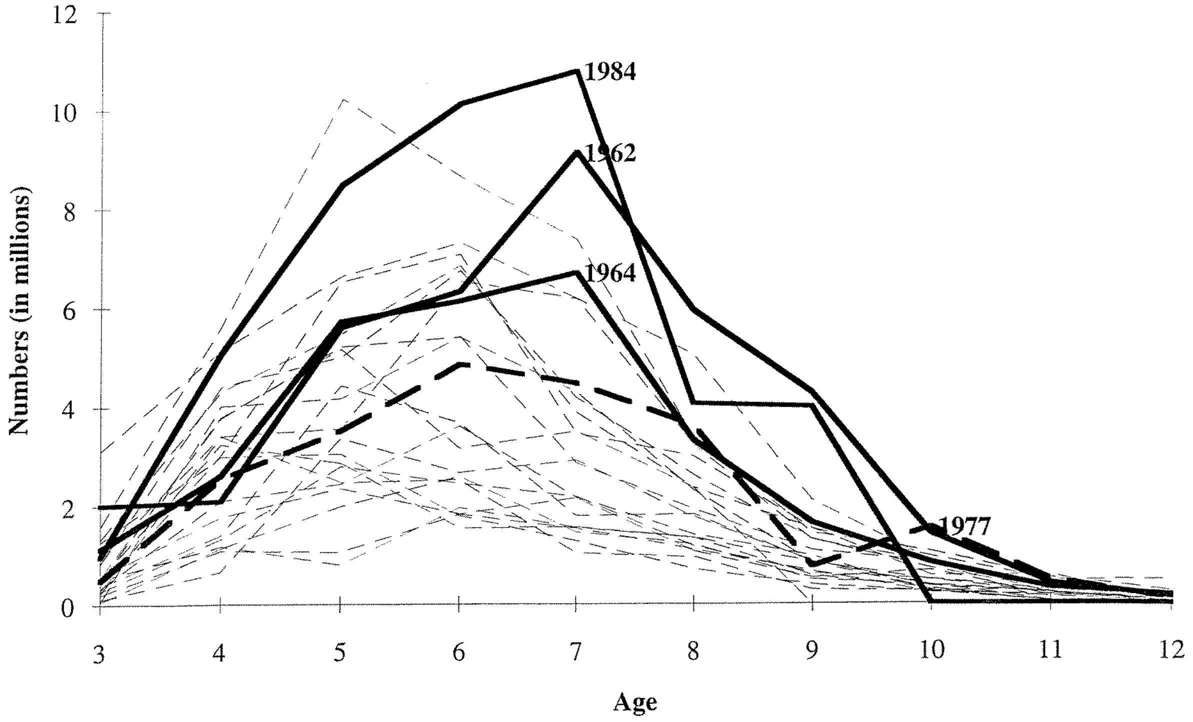


Figure 5.6. Catch at age for year classes of saithe at Iceland since 1962.


Numbers (in millions)
0
2
4
6
8
10
12
Age
3
4
5
6
7
8
9
10
11
12
1984
1962
1964
1977

[redacted]

Figure 5.6. Catch at age for year classes of saithe at Iceland since 1962.

Appendix

The mixture model and its variance

A number of statistical papers have dealt with the mixture model

$$g(x) = \pi_1 f_1(x) + \ldots + \pi_k f_k(x)$$

with π's and f's denoting the proportions and probability density functions of each of k components and $g(x)$ the probability density function of the resulting distribution mixture and various ways of estimating some or all of the parameters in the model (*e.g.* Day 1969; Dick and Bowden 1973; Hosmer 1973; James 1978; MacDonald and Pitcher 1979; Scnute and Fournier 1980). Few of them state explicitly a formula for the variance of a mixture of two components, which we need in the present case, when attempting to analyse the precision of the moment estimate of the mixing proportion, as suggested by Shepherd and Pope (1993). However, Johnson and Leone (1977), in a textbook example, give the general formula

$$VarX = \sum_{i=1}^{k} \pi_i \sigma_i^2 + \sum_{i=1}^{k} \pi_i (\mu_i - \mu)^2$$

for the variance of a mixture of k distributions with π_i, σ_i^2 *and* μ_i the proportion, variance and mean, respectively, of component i in the mixture and μ the mean of the mixed distribution itself given by

$$\mu = \sum_{i=1}^{k} \pi_i \mu_i .$$

For a mixture of two distributions the variance expression simplifies to

$$VarX = \pi\sigma_1^2 + (1-\pi)\sigma_2^2 + \pi(1-\pi)(\mu_1 - \mu_2)^2$$

when we have replaced the mixture mean with its formula in component means and $\pi=\pi_1$ and $1-\pi=\pi_2$.

The mixing proportion is given by

$$\pi = \frac{\mu - \mu_1}{\mu_2 - \mu_1}$$

where $\mu = \pi\mu_1 + (1-\pi)\mu_2$ is the mean of the mixed distribution. One way of estimating the mixing proportion, assuming knowledge of the means and variances of the components, given by James (1978), is equating the sample mean with the population mean which gives us

$$\tilde{p} = \frac{\overline{X} - \mu_2}{\mu_1 - \mu_2}$$

the so-called moment estimate of the mixing proportion which has an approximate large-sample variance

$$Var(\tilde{p}) = \frac{\pi(1-\pi) + [\pi\sigma_1^2 + (1-\pi)\sigma_2^2]/(\mu_1 - \mu_2)^2}{n}$$

In the following it will be shown how the variance of the moment estimator for the mixing proportion is derived from the variance in the mixed distribution.

The variance of the mean of a sample from a mixture is

$$Var(\overline{X}) = \left\{\pi\sigma_1^2 + (1-\pi)\sigma_2^2 + \pi(1-\pi)(\mu_1 - \mu_2)^2\right\}/n$$

for a sample of size *n*. The variance of the mean determines the variance of the mixing proportion completly when we assume component means and variances are known, namly

$$Var(\tilde{p}) = Var\left(\frac{\overline{X} - \mu_2}{\mu_1 - \mu_2}\right) = \frac{Var(\overline{X})}{(\mu_1 - \mu_2)^2} = \frac{\left\{\pi\sigma_1^2 + (1-\pi)\sigma_2^2 + \pi(1-\pi)(\mu_1 - \mu_2)^2\right\}/n}{(\mu_1 - \mu_2)^2}$$

which rearranges to

$$Var(\tilde{p}) = \frac{[\pi\sigma_1^2 + (1-\pi)\sigma_2^2]/(\mu_1 - \mu_2)^2 + \pi(1-\pi)}{n}$$

the formula given in James's (1978) paper.

We note that $Var(\tilde{p})$ can be regarded as the sum of the usual binomial variance and an addition due to the separation of the mixture components and their variances. This addition is the dominant term for the sets of numbers considered here as can be seen after making some simplifying assumtions. A further note is, that as the separation of the components increases this addition becomes smaller while it increases with the variance of one or both components. The variance of the mixture mean, on the other hand, increases with both separation and component variances.

Table I. Mean lengths at age for saithe year classes at Iceland.

	YCL70	YCL71	YCL72	YCL73	YCL74	YCL75	YCL76	YCL77	YCL78	YCL79	YCL80	YCL81	YCL82	YCL83	YCL84	YCL85	YCL86	YCL87	YCL88	YCL89	YCL90
AGE4	61.15	56.59	58.45	62.65	63.14	58.92	59.82	60.43	60.80	59.86	55.53	60.27	60.03	56.12	58.16	58.34	55.97	55.34	57.38	60.49	58.84
AGE5	73.41	69.04	68.05	70.85	68.29	66.73	66.32	69.26	69.11	69.06	69.08	68.43	65.16	64.41	62.42	64.51	62.93	64.94	66.26	67.16	
AGE6	81.45	79.72	78.45	78.49	77.17	73.85	70.39	78.12	78.50	76.67	78.41	75.53	73.17	70.60	69.50	70.93	71.66	74.37	74.02		
AGE7	88.55	86.13	84.07	86.57	79.61	84.65	76.76	84.83	82.99	85.71	82.98	82.64	80.36	79.31	75.94	78.41	79.47	82.93			
AGE8	92.04	91.09	91.28	89.30	90.55	89.41	80.06	90.51	90.88	90.61	89.30	88.43	89.52	86.48	82.73	86.29	86.87				
AGE9	95.96	95.64	92.91	95.81	98.33	95.27	87.55	96.38	95.78	97.38	94.46	94.90	94.14	90.49	84.47	93.38					
AGE10	101.23	99.92	98.79	103.08	100.96	99.76	90.75	100.18	101.15	101.87	100.38	98.03	96.32	93.34	90.29						

Table II. Numbers sampled by yearclass.

	YCL70	YCL71	YCL72	YCL73	YCL74	YCL75	YCL76	YCL77	YCL78	YCL79	YCL80	YCL81	YCL82	YCL83	YCL84	YCL85	YCL86	YCL87	YCL88	YCL89	YCL90
AGE4	528	278	223	179	300	542	249	223	194	361	218	383	270	615	520	460	337	170	682	322	740
AGE5	193	116	139	396	223	606	707	423	208	141	557	778	657	708	937	777	461	779	984	561	
AGE6	109	81	193	409	385	1054	824	326	187	377	767	910	582	884	1616	765	831	689	991		
AGE7	87	188	223	491	277	794	622	206	435	492	707	588	423	1007	1468	852	750	567			
AGE8	205	79	360	184	252	352	360	439	457	363	463	588	483	722	1036	781	524				
AGE9	27	135	68	223	87	55	428	269	187	184	275	336	305	327	1342	502					
AGE10	98	26	67	79	23	166	738	158	68	70	124	247	84	289	810						

Table III. Standard deviations.

	YCL70	YCL71	YCL72	YCL73	YCL74	YCL75	YCL76	YCL77	YCL78	YCL79	YCL80	YCL81	YCL82	YCL83	YCL84	YCL85	YCL86	YCL87	YCL88	YCL89	YCL90
AGE4	5.569	7.503	3.465	4.198	4.522	4.440	5.866	4.489	6.188	5.470	8.623	5.283	5.350	5.437	6.105	5.724	5.359	5.812	5.001	5.368	5.580
AGE5	5.711	6.368	9.097	4.817	5.295	6.703	6.249	5.273	6.204	6.684	8.739	5.085	6.964	6.817	6.602	5.658	5.620	5.746	5.653	5.879	
AGE6	5.860	7.342	5.589	5.630	8.964	5.874	7.867	5.529	6.139	6.921	6.814	5.631	7.229	6.336	8.383	6.651	5.696	5.990	5.810		
AGE7	5.064	5.648	5.805	6.112	7.637	4.677	8.464	5.477	6.625	6.109	6.603	6.628	6.819	7.320	8.467	6.616	6.066	6.038			
AGE8	4.488	5.311	5.060	5.586	5.297	5.965	8.116	6.491	6.130	6.403	7.303	5.638	6.498	7.047	8.008	6.335	6.654				
AGE9	4.670	5.673	7.911	4.514	5.636	7.799	8.652	6.283	5.991	6.517	6.432	5.831	6.176	7.122	7.397	6.627					
AGE10	5.167	7.260	4.794	4.741	6.491	7.287	6.513	6.274	6.299	6.808	7.368	6.256	7.015	7.340	8.262						

Table IV. Coefficients of variation.

	YCL70	YCL71	YCL72	YCL73	YCL74	YCL75	YCL76	YCL77	YCL78	YCL79	YCL80	YCL81	YCL82	YCL83	YCL84	YCL85	YCL86	YCL87	YCL88	YCL89	YCL90
AGE4	0.091	0.133	0.059	0.067	0.072	0.075	0.098	0.074	0.102	0.091	0.155	0.088	0.089	0.097	0.105	0.098	0.096	0.105	0.087	0.089	0.095
AGE5	0.078	0.092	0.134	0.068	0.078	0.100	0.094	0.076	0.090	0.097	0.127	0.074	0.107	0.106	0.106	0.088	0.089	0.088	0.085	0.088	
AGE6	0.072	0.092	0.071	0.072	0.116	0.080	0.112	0.071	0.078	0.090	0.087	0.075	0.099	0.090	0.121	0.094	0.079	0.081	0.078		
AGE7	0.057	0.066	0.069	0.071	0.096	0.055	0.110	0.065	0.080	0.071	0.080	0.080	0.085	0.092	0.111	0.084	0.076	0.073			
AGE8	0.049	0.058	0.055	0.063	0.058	0.067	0.101	0.072	0.067	0.071	0.082	0.064	0.073	0.081	0.097	0.073	0.077				
AGE9	0.049	0.059	0.085	0.047	0.057	0.082	0.099	0.065	0.063	0.067	0.068	0.061	0.066	0.079	0.088	0.071					
AGE10	0.051	0.073	0.049	0.046	0.064	0.073	0.072	0.063	0.062	0.067	0.073	0.064	0.073	0.079	0.092						