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A Framework for the Assessment of the Scotian Shelf and Southern Grand Banks Atlantic Halibut Stock

Cadre d'évaluation du stock de flétan de l'Atlantique du plateau néo-écossais et du sud des Grands Bancs

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ABSTRACT

The literature and data on Atlantic halibut was reviewed with the primary goal of supporting the first quantitative age-structured assessment of the Scotian Shelf and southern Grand Banks Atlantic halibut stock. The Canadian and foreign landings back to 1970 were used in the assessment. The catch at length was estimated using observer and port sampling data from 1988 for the longline fishery and from 1984 for the otter trawl fishery. The long-term average discard rate was used to estimate the total catch back to 1970. The total catch in the longline fishery was further divided into males and females based on observer data. A length-based, age-structured model was fitted to the length compositions in the catch and to the catch rate and length composition of halibut caught in the Scotia-Fundy groundfish Research Vessel survey (1970-2009) and halibut survey (1998-2009).

Simulation testing, model fit and model comparisons indicate that the catch at length (CAL) model was good for estimating stock size and the impact of the fishery. Model estimates indicate a high population biomass and recruitment in the 1970s, increased biomass, but poor recruitment in the 1980s, low biomass and recruitment in the 1990s, and increasing biomass and recruitment in the 2000s. The spawning stock biomass in 2009 was estimated at 6527t (2592t females only). Exploitation rates were about 0.2 for the longline and otter trawl fisheries in 1970, but rapidly increased to 0.4 or greater in the late 1980s and early 90s as the population decreased. Current fishing mortality is about 0.2 for the longline fishery, but in recent years there was increased pressure on females with fishing mortality of 0.30 compared to 0.14 for males in 2009. Fishing mortality from the otter trawl fishery has been low since the mid 1990s and in 2009 was estimated at 0.02. Candidate biological reference points were estimated from the catch at length (CAL) and virtual population analysis (VPA) models using the approach outline by Sissenwine-Shepherd (1987). Both assessment models gave similar results (BMSY=4900t, FMSY=0.36). Based on assessment model results, 3NOPs4VWX5Zc Atlantic halibut population is in a productive period due to high recruitment. The SSB is estimated to be in the healthy zone; above the BMSY. Current fishing mortality (0.2) is well below FMSY (0.36). Although catch projections were not made, recent high recruitment would be expected to result in higher SSB at the current fishing mortality rate in the near term. The proposed framework for assessing Atlantic halibut takes advantage of length frequency and catch rate data from multiple datasets and is both robust and effective in estimating stock status, the impact of the fishery, and the provision of management advice.

RÉSUMÉ

On a procédé à une analyse des documents et des données sur le flétan de l'Atlantique, qui avait pour but principal d'appuyer la première évaluation quantitative, structurée selon l'âge, du stock de flétan de l'Atlantique du plateau néo-écossais et du sud des Grands Bancs. Les débarquements canadiens et étrangers (remontant jusqu'à 1970) ont servi à cette évaluation. Les captures selon l'âge ont été estimées d'après les données des observateurs et les données d'échantillonnage au port de 1988 pour ce était de la pêche à la palangre et de 1984 pour ce qui était de la pêche au chalut à panneaux. Le taux moyen de rejets à long terme a servi à estimer les captures totales rétrospectivement jusqu'en 1970. Les captures totales dans la pêche à la palangre ont ensuite été réparties entre mâles et femelles, selon les données des observateurs. Un modèle fondé sur la longueur des captures et structuré selon l'âge a été calé sur la composition des captures selon la longueur, ainsi que sur le taux de captures et la composition, selon la longueur, des flétans échantillonnés dans le relevé par navire scientifique sur le poisson de fond de Scotia Fundy (1970 2009) et le relevé sur le flétan (1998-2009).

Il ressort des simulations, du calage des modèles et des comparaisons entre ces derniers que le modèle fondé sur les captures selon la longueur (CSL) produisait une bonne estimation de l'effectif du stock et de l'incidence de la pêche. Les estimations du modèle dénotent une forte biomasse et un recrutement élevé parmi la population dans les années 1970, une hausse de la biomasse, mais un piètre recrutement dans les années 1980, une faible biomasse et un faible recrutement dans les années 1990 et une hausse de la biomasse et du recrutement dans les années 2000. La biomasse du stock de reproducteurs en 2009 a été estimée à 6 527 t (2 592 t de femelles exclusivement). Le taux d'exploitation était d'environ 0,2 dans la pêche à la palangre et au chalut à panneaux en 1970, mais il a rapidement augmenté pour se situer à au moins 0,4 à la fin des années 1980 et au début des années 1990, alors que la population diminuait. La mortalité par pêche actuelle est d'environ 0,2 dans la pêche à la palangre, mais ces dernières années la pression exercée sur les femelles a augmenté et la mortalité parmi elles a été de 0,30 en 2009, comparativement à 0,14 chez les mâles. La mortalité par pêche dans la pêche au chalut à panneaux est faible depuis le milieu des années 1990 et en 2009 elle a été estimée à 0,02. On a établi des points de référence estimatifs d'après le modèle de captures selon la longueur (CSL) et d'après le modèle d'analyse de population virtuelle (APV), en suivant l'approche décrite dans Sissenwine Shepherd (1987). Les deux modèles ont produit des résultats semblables (BPME = 4 900 t, FPME = 0,36). Selon le modèle d'évaluation, la population de flétan de l'Atlantique de 3NOPs4VWX5Zc traverse une période productive en raison du fort recrutement. On estime que l'état de la BSR se situe dans la zone saine, au-dessus de la BPME. La mortalité par pêche actuelle (0,2) est bien inférieure à FPME (0,36). Bien qu'on n'ait pas effectué de projections de captures, au taux de mortalité par pêche actuel le fort recrutement récent devrait se traduire à court terme par une BSR plus élevée. Le cadre proposé pour l'évaluation du flétan de l'Atlantique tire parti des données sur les fréquences de longueur et sur les taux de captures provenant de multiples ensembles de données et c'est un outil à la fois solide et efficace pour estimer l'état du stock et l'incidence de la pêche, et pour formuler un avis sur la gestion du stock.

INTRODUCTION

This document presents a new framework for the assessment of the Atlantic halibut (*Hippoglossus hippoglossus*) stock on the Scotian Shelf and southern Grand Banks. The assessment model can be broadly described as a length- based, age-structured model. The model fits to the length composition of the catch from the longline and otter trawl fisheries, and to survey catch rates and length composition. The document was organized into three main sections: 1) data, including fishery, survey and life history data, 2) assessment model structure with equations and assumptions, and 3) assessment results with estimates of spawning stock biomass, fishing mortality and biological reference points.

LANDINGS

Atlantic halibut has been exploited in Eastern Canadian waters for more than a century (Fig. 1a). The earliest records show that most of the halibut catch was landed in Nova Scotia. From 1870 to 1910, 85% of the total landings were landed in Nova Scotia (477 metric tons; Table 1). Nova Scotia landings nearly tripled from 1911 to 1949 averaging 1273t, or approximately 95% of the reported landings. Landings increased dramatically in 1950 and 1951 to 5122 and 3475t respectively (Fig. 1a) and over 8000t in 1967 and 1968, but it was likely that Greenland halibut (i.e. turbot) and Atlantic halibut were not differentiated and these high values represent a mixture of landings of both of these species. With the creation of the International Commission for the Northwest Atlantic Fisheries (ICNAF) and later the North Atlantic Fisheries Organization (NAFO) landing statistics were reported in regions called sub-areas and divisions. The landings for what would eventually be defined as the Scotian Shelf and Southern Grand Banks (3NOPs4VWX5Zc) stock were 3780t in 1960 (Table 2, Fig. 2). Landings declined to 984t in 1974 and increased to 4109t in 1985. Until 1988 the fishery was unregulated, at which point a total allowable catch (TAC) of 3200t was implemented. The TAC remained at this level for six years during which landings declined. In 1994, the TAC was decreased to 1500t and the following year it was further reduced to 850t. A legal size limit of ≥ 81cm was also implemented in 1994. Since 1995, the TAC and landings have steadily increased and the TAC was set at 1700t for the 2010-2011 fishing year (Fig. 1b). The landings are primarily caught by Canadian fishermen using longline gear (Fig. 2). Foreign landings were high in the 1960s and comprised 20 to 30% of the catch, but declined in 1973 to 69t. In 1977, foreign effort was excluded from most of the stock area with the implementation of the 200 mile limit, with the exception of the tail of the Grand Banks (SE portion in 3N). In 2009, foreign catch was only ~1% of the landings (Fig. 3a). Canadian landings also declined over a slightly longer period up until 1975. Canadian landings increased in 1986 to approximately the 1960’s levels. Canadian landings declined and reached an all time low in 1994 but have steadily increased over the past 16 years (Fig. 2). The proportion of the landings caught by the longline and otter trawl fisheries was fairly even in the 1960s and 70s, but landings have primarily come from the longline fishery since 1980 (Fig. 3b).

LIFE HISTORY AND BIOLOGY

The Atlantic halibut is a large-bodied long-lived species that has captured the imagination and curiosity of fisherman and scientists. It is the largest of the flatfish species and is sexually dimorphic where females grow to a larger size than males. In Eastern Canada, the largest female on record was caught in 2004, measured 2.33m in length, and weighed approximately 173kg. The largest male was caught in 2003 and measured 2.13m.

Halibut are found throughout the coastal waters of Eastern Canada from depths less than 50m to more than 1,250m, but are typically caught between 200 and 450m. Males are caught in deeper waters than females ($p < 0.001$, Fig 4), but the difference of only 16m may not be biologically relevant. Our results are opposite to McCracken's (1958) conclusion, however, McCracken only examined relatively shallow waters (90 – 147m), and his sample size (n=185) was much smaller than ours (n=10,168). Both McCracken (1958) and Zwanenberg *et al*. (1997) concluded that larger fish preferred deeper water. Zwanenberg *et al*. (1997) examined a greater range of depths than McCracken (1958) but the relationship was weak, possibly because the research survey use an otter trawl which selects for smaller halibut. A cursory examination of fisheries data (longline and otter trawl combined) indicates that there was little depth preference by size (Fig. 5). It is well known that halibut prefer cold water along the edge of the continental shelf, typically within a few degrees of 5°C (Neilson *et al*. 1993, Bowering 1986). Preliminary work using pop-up satellite tags confirms this habitat preference.

Large halibut can be extremely fecund. A 90.7kg female may produce over 2 million eggs (Lonning *et al*. 1982) and in another study a 195cm female produced ~7 million eggs (Haug and Gilliksen 1988). Current data on the size at maturity of fish on the Scotian Shelf or the southern Grand Banks are lacking, older work in the region found that females reached 50% maturity at about 119cm (total length), while males reached 50% maturity at about 77cm (Trumble *et al*. 1993, Table 3). Recent work in the Gulf of St. Lawrence found that fish matured at a slightly smaller length (Archambault 2007, Table 3). Using our growth data (described below) and the length at maturity from Trumble *et al*. (1993) we estimated that females and males reach 50% maturity at 9 years, and 5 years of age, respectively.

Halibut are long-lived. The oldest halibut observed was a 50 year old male (Armsworthy and Campana 2010), however, individuals over 25 years old were rare in our collection. Natural mortality should be less than 0.2 in order for individuals to reach this age. In this assessment, we assumed a natural mortality of 0.1.

POPULATION ASSESSMENT HISTORY

The assessment of Atlantic halibut has gone through several stages. The first stock assessment was by Perley *et al*. (1985), where they examined distributional patterns, patterns in exploitation and a commercial catch per unit effort (CPUE) index. The recommendation for the Scotian Shelf and southern Grand Banks management unit was made by Neilson *et al*. (1987) based largely on the tagging study by Stobo *et al*. (1988). Neilson *et al*. (1987) also compared length/weight relationships and growth rates and concluded that the Gulf of St. Lawrence was a separate stock. Neilson and Bowering (1989) examined the effect of a minimum size limit on yield and concluded that a minimum legal size of ≥81cm would not have a significant effect on yield unless natural mortality was low (~0.1). A minimum legal size of ≥81cm was adopted on an interim basis in 1988, and was 'enforced' in 1990, but Annand and Beanlands (1993) commented that the minimum size limit was not strictly enforced. In the observed portion of the otter trawl fleet, enforcement only became strongly apparent in 1994 when the length frequency of kept individuals became truncated. Annand and Beanlands (1993 and 1996) examined the catch rate of halibut in the groundfish research trawl survey (RV), and commercial fishery (CPUE) and recommended a decrease in the TAC based largely on low catch and decreasing catch rates. Zwanenberg *et al*. (1997) provided the first in-depth review and analysis of halibut data: landings, distribution, catch rate of several groundfish RV surveys, CPUE for the commercial fishery, and estimates of total mortality. In particular, they demonstrated that there was a reduction in the number of larger individuals from 1960's to the 1990's. From these data, they estimated that Z increased from 0.32 in the 1960's to 0.51-0.53 in the 1990's. Their yield per recruit analysis resulted in $F_{0.1}$ = 0.08 and F_{max} = 0.24. Assessments up to 1997 relied heavily on fishery data and the RV survey data which typically catches only 40 to 70 small (30 to 70 cm) halibut per year. In response to the lack of data on larger halibut, a joint industry/DFO halibut survey was initiated in 1998. Assessment and science advice from 1998 to present have relied heavily on the trends in the halibut survey (e.g. Trzcinski *et al*. 2009).

This framework assessment attempts to take full advantage of the wealth of data generated from the halibut survey. In particular, the halibut survey produces estimates of annual catch rate and length composition. Further, joint industry/DFO projects on halibut ageing and tagging were also made possible through collaboration with the Atlantic Halibut Council, a consortium representing the industry. The principal sources of data for this framework assessment are the length composition in the catch, ageing data, the catch rate in the halibut survey and in the Scotia-Fundy groundfish RV survey. It should be noted that the data have limitations inherent in the biology of the species (long-lived, large, highly mobile). Cohorts can only be followed in the RV survey for the first few ages. The halibut survey catches larger and older individuals, the segment of the population we are principally interested in, but cohorts are not distinguishable. The model integrates these datasets.

MANAGEMENT UNIT AND TAGGING

The current management unit for Atlantic halibut on the Scotian Shelf and southern Grand Banks (3NOPs4VWX5Zc) is the largest of any groundfish in Canadian waters (Fig 6). Early tagging studies found that halibut could move long distances as two fish tagged off of Anticosti Island were recovered in Icelandic waters (Martin and McCracken 1950), and 4 of 8 fish tagged in Iceland were recaptured in Canadian waters (Trumble et al. 1993). Many groundfish, including Atlantic halibut were tagged in the early years of the ICNAF and NAFO organizations to help define stock boundaries. Stobo *et al*. (1988) found that Atlantic halibut moved long distances, which provided the basis for the current management unit. Between 1953 and 1973, 290 tags were recovered out of 1296 tagged halibut, for a recovery rate of 22.4% (Stobo and Fowler 2006).

A joint Industry/DFO tagging study was initiated in 2006 and halibut were tagged and released in 2006, 2007 and 2008. This study was more rigorously implemented as fishermen were allocated a given batch of tags, tagging was done by observers and in proportion to abundance, fish of all sizes were tagged, all fish were double tagged, fishermen were compensated for releasing legal size fish, and a reward of $100 was given for returned tags. Analyses of these data, including estimates of fishing mortality are presented in Den Heyer *et al*. (2011). Estimates of fishing mortality based on tagging provide an independent ‘check’ of the assessment model results.

Here we analyze the release and recovery location of 2064 halibut tagged on the Scotian Shelf and southern Grand Banks. A total off 411 halibut were recovered. Halibut were generally recaptured in the same NAFO division in which they were tagged, with only 12 recaptured in the Gulf of St. Lawrence (4RST, Table 4). An analysis of the Gulf of St. Lawrence tagging program show similarly low levels of interchange (Table 5).

Recent tagging in the Gulf of Maine indicates considerable transboundary movement, as 33% of the recaptured halibut were caught in Canadian waters (Kanwit 2007, Col and Legault 2009). However, none of the halibut tagged between 2006 and 2008 on the Scotian Shelf and southern Grand Banks were recaptured in US waters. Overall, it appears that the management unit is supported by the current tagging data.

FISHERIES DATA

Despite the economic importance of Atlantic halibut, onboard observer and port sampling have been sparse. The number of trips observed on the otter trawl fleet peaked during the collapse of the cod fishery, and then rapidly declined averaging 20 trips/year from 1997-2007. Only a few halibut fishing trips were observed from 1988 to 1995, averaged 17 trips from 1996 to 2009 but only 8, 6 and 10 trips were observed in 1997, 2004, and 2006 (Fig. 7). Seasonal coverage of the otter trawl fleet (1977-2007) peaked in April and steadily declined through the rest of the year, whereas longline coverage from 1988-2009 was highest in January, and lowest in autumn (Fig. 8). In the last three years, only 0.2% of halibut landings by the otter trawl fleet are observed (by weight), whereas 11.7% of the longline landings are observed.

The groundfish port sampling program started in 1948, but halibut were not measured because most fish were landed with their head off. Halibut length was first recorded in our port sampling database in 1989. Between 0.007% and 0.53% of the landings by the otter trawl fleet were port sampled. On average, 0.28% of the halibut landed by longline fishermen were port sampled prior to 1998. When the halibut survey started in 1998, the majority of commercial index landings were port sampled, and the percentage of the landings port sampled increased to 3.6% on average. Table 6 presents a timeline of changes in the halibut fishery data.

The catch-at-length is one of the most important data inputs to this assessment model. However, a full catch-at-length has not previously been estimated for Atlantic halibut. Zwanenberg *et al.* (1997) examined the length composition for the longline catch in 1960 and both the longline and otter trawl catch from 1994 to 1996.

The catch-at-length was estimated using various assumptions about what the available samples represent in the context of overall landings. The accuracy of the resulting catch-at-length is ultimately determined by the degree to which natural variation in the catch (in time, space, length) was properly sampled. Both observer and port samples are used to estimate the catch-at-length in the otter trawl and longline fishery. However, the legal size limit of ≥81cm implemented in 1994 poses certain problems. The proportion of the catch <81cm on observed trips is plotted in Fig. 9. Approximately 2% of the longline catch and 35% of the otter trawl catch was less than 82cm. One of two approaches can be taken, either observer samples after 1993 are truncated and the catch at length for the landings is estimated, or observer samples are used to prorate the port samples and a catch-at-length for the total catch including discards is estimated. The latter is a better estimate of the total impact of fishing and was the method used in this assessment. A catch-at-length was built separately for males and females in the otter trawl and longline fisheries.

Catch-at-length was constructed as follows: 1) observer samples at length were extrapolated to the trip catch, 2) the trip-level length frequency and parameters from a length-weight relationship (annual for recent years and in blocks for older years) were used to estimate the trip weight of all fish caught including discards, 3) the proportion of the catch <81cm was calculated for the years 1994-2008, 4) port samples were prorated by estimating the weight of fish which would have been caught and discarded from observer data, 5) the estimated discard weight was divided by the average weight of a fish at length to estimate the numbers of discards at length for port sampled trips, 6) the resulting observer and port sampled length frequencies were combined using a weighted average, 7) the combined length frequency was extrapolated to the total catch, finally 8) unsexed fish in the longline samples were allocated to males and females based on the sex ratio at length (Figs. 10).

The percent of unsexed samples in the observed longline fishery was high and quite variable up until 2000 at which time it stabilized at about 10% (Fig. 11). An overall catch at length for otter trawl fishery was calculated and not divided into males and females. Figures 12 and 13 plot the weight measured (observer and port samples combined) over time and the landed / measured weight (‘bump-up’ factor) for the longline and otter trawl fishery. The estimated of total catch, including discards, is shown in Figure 14. Approximately 1/3 of the catch (by weight) are males and 2/3 are female (Fig. 15), but approximately equal in numbers. The resulting length frequencies and the corresponding proportions at length which are used to fit the assessment model are presented in Appendix A.

The average size of halibut caught by the fishery has changed over time. The long-term mean size of halibut caught by otter trawl gear since 1984 was 85.4cm. The mean length in the otter trawl catch was 99cm in 1984, decreased to 64cm in 1990, increased to 100cm in 1997, and has averaged 86cm since. A larger proportion of small fish were caught in 2000 and 2004 (Fig. 16). The mean length of males and females in the longline catch was high in 1988 (102 and 128cm respectively), decreased to a low in 1996 (87 and 100cm), steadily increased to 2007 (99 and 135cm), and dropped to (93 and 111cm) in 2009. The long-term means for males and females are 95.7 and 113.6cm respectively (Fig. 16). The means sizes of halibut in the catch are clearly influenced by changes in the fishery, but probably also reflect changes in the size composition of the population.

INDICES OF ABUNDANCE

There are several indices of abundance examined in this assessment. The most important is the summer Scotia-Fundy groundfish RV survey (RV survey) and the halibut survey. The Newfoundland groundfish RV surveys (NL spring and autumn RV survey), and the halibut commercial index are not currently incorporated into the assessment model. This was done 1) to simplify the model, 2) because the NL spring and autumn RV survey estimates are not expanded to the total abundance on the southern Grand Banks, and 3) because the commercial index has not been standardized for area and vessel effects.

The RV survey has been conducted every July since 1970. Each year, about 231 fishing stations are sampled from the Upper Bay of Fundy to the northern tip of Cape Breton and offshore to the 400 fathom contour (approximately 700m) (Branton and Black, 2004). The median size of halibut caught in the trawl survey was between 40 and 50 cm. There has been some variation from year to year such as the number of strata covered, the length of the survey, and different vessels used. Perhaps most importantly, the fishing gear was changed from a Yankee-32 to a Western-2a in 1982. While this variation was known to have important effects on the catchability and catch rates of cod and haddock, it appears to have had little effect on halibut. There was no discontinuity in either the number or the size of halibut caught before and after 1982. Fanning (1985) estimated conversion factors for nine fish species caught in the summer RV survey. He found that no conversion factor was necessary for American plaice >28cm. We might expect the catchability of large plaice (a similar flatfish) to be similar to small halibut. Based on this assumption no correction factor was applied. The area expanded total number of halibut caught per year was used as an index of abundance (plot and model fit in Results section).

The halibut survey has been conducted from 1998 to present and has provided an important source of information on a broader size range of halibut (50-230cm). The survey has a fixed station design and in 1998, 222 stations were allocated to strata based on the previous two years of commercial catch and the goal of wide spatial coverage (note: catch *rate* was not used). Some rearrangement and reallocation of stations occurred in 1999, based on logistics and whether stations were assigned to the proper strata. A total of 73 stations were added from 2005 to 2008 to increase coverage in the Bay of Fundy and north of Cape Breton. Fishermen are asked to follow fishing protocols (minimum distance from a station, hook-size, number of hooks, and minimum soak times) (Zwanenburg and Wilson 2000a, 2000b, Zwanenburg *et al*. 2003), however there still was some variation in survey protocol, which could affect catch rates. During the same time period, fishermen also contributed to a commercial index where they fish at locations of their choosing. Participants tend to use the same protocol as the survey, but again there was some important variation in protocol (putting out more hooks, soaking longer, variation in bait, etc). To date, the effects of variation in fishing practice during the halibut survey and commercial index have not been fully examined. However, the effects of station coverage and the duration of vessel participation have been examined in the halibut survey (Trzcinski *et al*. 2009). Not all stations in the halibut survey were fished each year compromising the coverage and statistical rigour of the survey. Survey results have been analyzed many different ways in an attempt to account for variable station coverage (*e.g.* Armsworthy *et al*. 2006). Since 2006, the stratification scheme has not been used in calculating an overall index of abundance, because of concerns over its current utility in reducing the variance in catch rates estimates. Most recently, catch rates were standardized using a generalized linear model by estimating station effects and disregarding the previous stratification scheme (Trzcinski *et al*. 2009). Although it was clear that more work needs to be done regarding the stratification scheme and the future design of the survey, the data were reanalyzed as in Trzcinski *et al*. (2009) and the standardized catch rate was used as an index of abundance in the assessment (Fig. 17a). The commercial index was simply standardized to 1000 hooks and 10 hours soak time, and was presented for comparison (Fig. 17b).

Length composition data from the RV survey and the halibut survey provide some data on population size structure, recruitment and changes in fishing pressure. These data components are also included in the assessment model. The length frequency and proportions at length can be found in Appendix A.

AGEING DATA

Atlantic halibut otoliths have been collected intermittently from 1946 to present (McCracken 1958, Armsworthy and Campana 2010). Typically less than 100 otoliths were collected per year between 1960 and 1987. Otoliths were collected primarily on research surveys and commercial trips using otter trawl gear. The collection increased to approximately 800/year from 1988 to 1998, as observers collected data on halibut caught on longline gear. Since the halibut survey started in 1998, approximately 2000 otoliths have been collected annually.

Although a number of studies have reported halibut age and growth in the past, most or all were based on ageing methods which are now considered to be unreliable. McCracken (1958) found that females grew to larger sizes than males and that growth rate slowed with age. Studies by Perley *et al*. (1985) and Bowering (1986) did not find evidence of asymptotic growth, but the oldest fish in their sample was only 12 and 16 years old, respectively. Bowering (1986) and Neilson *et al*. (1987) compared the size at age from fish collected on the Scotian Shelf and Newfoundland. Bowering (1986) concluded there was no difference, whereas Neilson *et al*. concluded that the size at age was slightly larger for fish on the Scotian Shelf. Ageing data were used by Zwanenberg *et al*. 1997 to estimate total mortality in the 1960's and mid 1990's and they found that the total mortality was higher in the 1990's as the size at age distribution was more truncated. They assumed a natural mortality of 0.2 probably based on a maximum age of 20 years. No ageing of Atlantic halibut occurred between 1988 and 2006, at which point DFO and the Atlantic Halibut Council initiated a new ageing study. This work is presented in

Armsworthy and Campana (2010), and was the first to provide independent confirmation of the accuracy of their age estimates.

Armsworthy and Campana (2010) selected otoliths from a broad range of lengths from fish collected on the RV survey and from commercial trips using otter trawl or longline gear from two periods: historic (1964-1974) and recent (1997, 2001 and 2007). They found that males and females grew at a similar rate until about age 5 after which male growth slows. Males averaged approximately 125cm and females averaged approximately 200cm after age 20 (Fig. 18). The standard deviation of length at age increased from age 2 to age 5 for both males and females, and then stabilized (Fig. 19). Halibut were found to live up to 50 years, and the growth rate did not change significantly between the historic and recent periods (Armsworthy and Campana 2010). Consequently, the assessment model assumes growth is constant from 1970 to 2009. Large temporal changes in growth have been observed in Pacific halibut (Clark *et al*. 1999), so it will be important re-evaluate this assumption every 10 years or so with new aging data, or when a large retrospective pattern occurs. Armsworthy and Campana (2010) found large differences in the length at age between halibut caught on longline and otter trawl gear, but relatively small differences in length at age between the Scotian Shelf and Grand Banks. The current model does not take into account the effect of gear on length at age beyond using different selectivities. It is recommended that the gear effect on the length at age be incorporated in future model runs.

ASSESSMENT MODEL

METHODS

The assessment model used in this framework can be broadly described as a length-based, age-structured model. The primary input to the model was length frequency data and several abundance indices. The model converts the lengths to ages using the ageing information and its associated variability. The population dynamics then becomes age-based (i.e., processes such as recruitment, maturity, selectivity, fishing and natural mortality occur at age). The model then predicts the catch rate in the abundance indices and the length frequency in the surveys and commercial catch. These predictions are then fitted to the data by minimizing the logliklihood. The model was written in AD Model Builder, which uses automatic differentiation to fit non-linear models to multiple data sets.

More specifically, the model is a forward-projecting age- and sex-structured population dynamics model similar to that of Gibson and Campana (2005). Total mortality was partitioned into natural mortality (M) and fishing mortality (F). Natural mortality was assumed to be 0.1 based on halibut longevity, although it was recognized that the natural mortality rate might be higher. The catch was extrapolated to total removals based on the annual estimate of the proportion discarded. Total removals were then assumed to be known without error. A discard mortality of 23% was assumed based on the study by Neilson *et al*. 1989 and was applied within the model. The annual fishing mortality was estimated iteratively using the Baranov equation. We assumed that fishing mortality could be separated into the selectivity of the commercial fishery and an annual fishing mortality (Quinn and Deriso 1999). The selectivity of the longline fishery was assumed to be asymptotic (logistic), and the selectivity of the RV survey and the otter trawl fishery and were assumed to be double-half Gaussian. Recruitment was estimated as a random walk assuming lognormal errors with a high variance (σ = 0.5). This variance was slightly lower than the estimated variance when recruitment was treated as a free parameter (σ = 0.67). The model fits to the observed proportions at length in the male and female longline catch, the otter trawl catch, and the halibut and RV survey. The model also fits to the abundance indices of the RV and halibut survey. The equations for the model can be found in Table 7.

The datasets used in the assessment model are summarized in Table 8. The model was initialized in 1970 by estimating the number of age 1 fish. Ages 2 to 20 are then 'filled in' using an assumed total mortality (Z) of 0.2. Sensitivity to the starting values is discussed in a following section. The only data available on halibut abundance from 1970 to 1984 is the RV survey data (abundance index and length composition), and the landings without length composition data. Data on the length frequency in the otter trawl catch starts in 1977 but sampling was very low in the first five years so we only used length frequency data starting in 1984. Data on the length frequency in the longline catch starts in 1988. So, the model was much better informed as one proceeds from 1970 to present. The influence of each dataset on the estimate of population size was partially affected by the amount of process error. Here we assume reasonable values for the variation (σ and sample size) based on our understanding of the data (Table 8). Coming up with natural weighting or effective sample size is a longer-term goal. The model has several constraints to speed convergence and keep the estimates within reasonable bounds (Table 9). Fishing mortality values greater than 1.0 were penalized. Recruitment to age 1 was assumed to be a random walk with lognormal error and a σ = 0.5, which is large enough to allow for a lot of variation in recruitment. Since recruitment is always difficult to estimate in the terminal year, recruitment in 2008 and 2009 was assumed to be the geometric mean of the previous three years. The fit of the model to the data is then the penalized-loglikelihood of the data given the model. The model was run out to 2009.

During the exploration of the model and data, it was noted that the periodic catch of small or large fish had strong leverage on the fit to the length composition data. Initially all the length data from 10 to 235cm were used and the model run out to age 40, but model fit improved as the tails of the length data were truncated and if the model only ran out to age 20. Trial and error showed that truncation of the data produced the best residual patterns. Lengths from 10 to 130cm were used from the otter trawl and RV data. Lengths from 41 to 160cm for males and from 41 to 187 for females were used from the longline data. Three points had an overly large effect on the model fit and appeared to be data errors. In 1988, 710 females between 58 to 61cm and 71 females between 46 and 49cm were estimated in the longline catch. In 1990, 14,400 halibut from 16 to 19cm were estimated in the otter trawl catch. Deleting these values improved the fit but had little effect on our estimates (SSB decreased by 9t, a 0.16% decrease).

MODEL TESTING

The model was tested using simulated data. An assumed longline fishery landed fish following Figure 20 with proportions at length as in Figure 21a. Estimated selectivities and numbers at age are in Appendix B. The simulated RV and longline survey caught fish as in Figures 22, 21b and 23. There was little bias in the model estimates as seen in Figure 24 where the lines in color represent the true values and the black lines represent the model estimates. The model accurately reproduced the pattern in fishing mortality (Fig. 25).

ASSESSMENT RESULTS

The parameter estimates for the model are listed in Table 10. By and large the model parameters are well estimated as the CVs are under 5%. Several parameters could not be estimated and were fixed at values listed in Table 10. These included the otter trawl selectivity parameters and the shape parameters for the longline fishery and halibut survey selectivities. These were set at values which effectively make the selectivity knife-edged (Fig. 26). It was assumed that halibut are fully selected to the otter trawl gear at age 5, corresponding to ~58 to 61cm. For longline gear, halibut were 50% selected at age 5.5 and 5.9 for males and females respectively, which corresponds to ~83 to 85cm (Fig. 26). Annual fits of the model to the male and female proportions at length and associated residuals plots can be found in Appendix C. Monte Carlo Markov-Chain (MCMC) simulations indicate that the parameters were fairly well estimated and the mode of the posteriors were close to the maximum likelihood estimates (e.g. Appendix D).

The fits to the abundance indices are shown in Fig. 27. The fit to the RV survey was fairly good with a short string of positive residuals in the late 1980s and early 90s. Survey estimates for 2010 were not fit in the model, but shown for comparison. The 2010 RV survey estimate was the highest on record and indicates high recruitment. Catch rates in the halibut survey increased from 2003 to 2009, decreased in 2010, but was still the second highest catch rate on record (Figs. 17, 27).

Atlantic halibut population dynamics, as estimated by the assessment model, show high biomass and recruitment in the 1970s. Biomass increased as fish grew and survival was good, but recruitment dropped and was relatively low in the 1980s and 90s (Fig. 28). During this period, biomass peaked at 13,300t in 1983 then decreased rapidly to 3750t in 1993. Biomass increased steadily since 1993, but recruitment remained low for several years. Recruitment has been above average since 2002 and was estimated to be between 280,000 and 480,000 age-1 recruits (Fig. 28). The plot of stock-recruitment shows that recruitment was highest when spawning stock biomass was between 3000 and 5000t in the 1970s and 2000s, and lowest when biomass was lowest (<3000t) in the 1990s (Fig. 29). A plot of the numbers of females at age shows a large recruitment pulse in the 1970s which died out by age 10 or 12, and similar recruitment in the 2000s (Fig. 30). The SSB in 2009 was estimated at 6527t (2592t females only).

Exploitation rates were about 0.2 for the longline and otter trawl fisheries in 1970, but rapidly increased to 0.4 or greater in the late 1980s and early 90s as the population decreased (Fig. 31). Current fishing mortality was about 0.2 for the longline fishery, but in recent years there has been increased pressure on females with a fishing mortality of 0.30 compared to 0.14 for males in 2009 (Fig. 31). Fishing mortality from the otter trawl fishery has been low since the mid 1990s, and in 2009 was 0.02. Fully-recruited fishing mortality estimates from the assessment model were comparable to estimates from tagging (Den Heyer *et al*. 2011; F = 0.20, 0.29, 0.21 for 2007, 2008 and 2009).

Residual plots of the RV survey proportions at length do not show year or length effects, but there are a few large positive residuals at the larger lengths (Figs. 32 and 33). Some strong residual patterns are evident in the proportions at length in the longline fishery (Fig. 34 and 35), indicating that selectivity at age did not capture the dynamics in the length composition data. However, there are no major year effects. The residual proportions at length do not show any major year or length effects after fitting to the otter trawl data (Fig. 36). The contribution of each data set to the overall fit of the model, as expressed as the proportion of the total likelihood is shown in Table 11.

SENSITIVITY AND MODEL COMPARISONS

Profiles of two parameters were examined by fitting the model to a fixed value and plotting the objective function (penalized log likelihood). There appears to be little information in the RV and halibut survey or the catch composition data to determine natural mortality. The likelihood surface was quite flat. Consequently, we assumed a value of 0.1. Similarly, the profile for the starting Z value used to initialize the model was flat, indicating that the data are not informative in estimating this parameter. It was fixed at 0.2.

All models make assumptions about the data and the underlying processes that produce the patterns in the data. One way to provide a check on these assumptions and find out how much the results are driven by the data, as opposed to the assumptions, is to compare models results. The results of the catch at length (CAL) model used in this assessment were compared to a statistical catch at age (CAA) and a virtual population analysis (VPA). These models make many different structural assumptions which will not be reviewed here. A primary assumption was that they assume that fish age was known without error. The VPA makes the further assumption that the catch was known without error. For this comparison, the dimorphic differences in growth were ignored and all the catch was attributed to the longline fishery. Both models were fit to the RV and halibut survey data. The three models gave surprisingly similar estimates of SSB and F (Table 12, Fig. 37, model fits in Appendix E and F). The 2009 estimates of SSB (males and females) were 6527, 5280, and 5790t for the CAL, CAA and VPA models respectively. The largest differences occurred when there was no catch data in the 1970s and 80s and consequently depends on the assumptions about how to use the landings. The CAL estimated fishing mortality in 2009 was 0.20 (0.14 for males and 0.30 for females). The CAA model estimated a fishing mortality of 0.17 and the VPA model estimated a fishing mortality of 0.18 for fully selected fish (> age 6) in 2009. There is also close agreement (except for 2008) in the CAL estimated fishing mortality and independent estimates of fishing mortality from a tagging study (Fig. 38, Den Heyer *et al*. 2011). The overall coherence of these results from four very different approaches should lend confidence to the current framework and results.

REFERENCE POINTS

A modified Sissenwine-Shepherd (1987) model was run to estimate the MSY and related parameters using output from the CAL model described above. Forty percent and 80% of BMSY were chosen as the upper and lower references. The biomass metric used was SSB (as opposed to total or fishable biomass). Similarly, FMSY was chosen for the fully recovered fishing mortality.

The methods used to investigate biological reference points and trial harvest control rules follow Mohn *et al*. (2009). The basic Sissenwine-Shepherd model fits a stock-recruit relationship and then infers the production curve (MSY, BMSY etc) from it using growth and survivorship. The modification made by Mohn *et al*. (2009) was to fit the production data as well, using a Shaeffer production model. Thus the output gives two insights into equilibrium production. The underlying inputs and equilibrium fits are shown in Figure 39. The black lines are the equilibrium yields from the stock-recruit data and are those developed by Sissenwine and Shepherd. The red line is the equilibrium fit using the surplus production data.

The MSY, SSBMSY and FMSY based on the stock recruit data are 1.5, and 4.9kt and a fully recruited F of 0.36. Those from the production data are similar but with a higher MSY (2.5kt) at a higher SSBMSY (11.8kt) suggesting a more productive population. We will not use the production based estimates any further as they were just presented to show the general agreement in the different types of information used inputs.

If the upper and lower biomass limits were defined as 40% and 80% BMSY from the production based estimates, a trial harvest control rule can be produced. These limits may be compared to the history of the SSB in Figure 40. The stock was between these two limits for most of the last 20 years and just recently crossed into the “healthy” zone. Similarly, the fishing limit is shown relative to the fishing mortality in Figure 41. From about 1988 to 1993 the fishing mortality was well above this reference level.

Figure 42 combines these references into a simple harvest control rule using the trial limits and the FMSY derived above. The points in the plot show the history of the SSB and F. Currently, the code for making projections from the CAL model does not exist. Dr. Mohn developed code for making projections from the VPA model. As seen in Figure 37 the VPA and CAL models correspond well since 1985. Projections for the next three years assuming removals of 2000t per year are shown in Appendix F. The ellipses represent uncertainty with the axis in each dimension being a single standard deviation. Removals of 2000t a year leave the stock expanding and well within the healthy region.

When agreement among Science, Management and stakeholders has been reached, biological references can be determined from the model outputs for this stock. Until then, Figures 39-42 and Appendix F remain as an example of how such information can be used.

DISCUSSION

Atlantic halibut data have been reviewed with the primary focus on how it would be used in a new assessment framework. The model incorporates male and female growth and dynamics, abundance indices from the RV and halibut survey, and catch length composition data. The model provides unbiased estimates of stock size and fishing mortality, despite low sampling of the fishery and large variation in the data.

Given the current level of sampling, the catch-at-length was probably as good as it can get in the near term. The catch-at-length could be improved in the future by including observer and port sampling data from Newfoundland. As pointed out earlier, observer coverage in the otter-trawl fishery was low and coverage needs to increase if catch-at-length in the otter-trawl fishery is to continue to be included in the assessment model. Although males and females grow at different rates, sex differences appear to have little influence on the selectivity-at-age but can have a large effect on estimates of fishing mortality. Model comparisons show removing sex-specific parameters was one way to simplify the model, but this may mask potential harm to the breeding stock, as the impact of the fishery was greater on females than males.

Armsworthy and Campana (2010) did not find temporal differences in growth, but it is important to test for growth differences in the future; as such difference could have important implication on yield. The ageing data used in this analysis resulted from a joint effort by industry and DFO. Otoliths continue to be collected, but ageing is not done every year. It is suggested that samples be collected annually and that changes in growth be examined every 5 to 10 years, or when model performance indicates that further testing is required.

The model presented captures the overall dynamics of the population and characteristics of the fishery. That is, it tends to capture the changes in landings, it fits the abundance indices well and does a reasonable job fitting the length-frequency data. A greater confidence in the model results was gained by comparison the results of a VPA, a statistical catch at age model (CAA). Another check on the model's performance was the tagging data which produces similar estimates of fishing mortality. Based on the fit to the data and broad agreement among different assessment approaches, it is concluded that the model provides a useful framework for the assessment of Atlantic halibut, is free of serious errors, and is effective in providing results useful to management.

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Table 1. Landings (metric tonnes) of Atlantic halibut by Province, 1867-1951. NS = Nova Scotia, NB = New Brunswick, QC = Quebec and PEI = Prince Edward Island. Since 1951 these four provinces comprised Statistical Area (SA) 4. Newfoundland landings are recorded in SA 3. Newfoundland landings prior to 1951 were not included because it was believed that Greenland halibut (a.k.a. turbot) and Atlantic halibut were combined when reporting statistics.

Year	NS	NB	QC	PEI	SA 4	SA 3	Total
1867	.	.	33	.	33	.	33
1868	.	.	18	.	18	.	18
1869	54	.	42	.	95	.	95
1870	139	.	21	.	160	.	160
1871	231	691	29	.	951	.	951
1872	.	.	37	.	37	.	37
1873	243	58	42	.	342	.	342
1874	260	8	28	.	296	.	296
1875	253	7	18	.	278	.	278
1876	427	33	17	.	477	.	477
1877	303	55	21	0	379	.	379
1878	315	67	26	1	408	.	408
1879	.	.	25	.	25	.	25
1880	404	123	20	1	547	.	547
1881	.	.	24	.	24	.	24
1882	341	105	32	3	481	.	481
1883	435	13	22	2	472	.	472
1884	660	19	24	3	706	.	706
1885	677	21	28	3	729	.	729
1886	622	25	21	4	673	.	673
1887	537	23	37	4	601	.	601
1888	450	8	48	4	510	.	510
1889	524	22	41	2	589	.	589
1890	312	47	42	2	403	.	403
1891	508	173	37	3	721	.	721
1892	708	175	57	10	950	.	950
1893	497	92	73	2	665	.	665
1894	553	108	62	4	727	.	727
1895	484	111	56	3	653	.	653
1896	462	98	73	1	633	.	633
1897	447	57	42	2	549	.	549
1898	742	50	78	5	874	.	874
1899	668	33	75	2	778	.	778
1900	744	41	86	4	875	.	875
1901	364	55	72	2	494	.	494
1902	559	58	82	2	701	.	701
1903	437	58	53	1	549	.	549
1904	425	56	66	.	547	.	547

Table 1. (Continued)

Year	NS	NB	QC	PEI	SA 4	SA 3	Total
1905	670	60	49	.	779	.	779
1906	420	66	80	0	566	.	566
1907	385	70	124	.	578	.	578
1908	604	71	97	.	772	.	772
1909	571	51	69	1	692	.	692
1910	751	57	41	0	849	.	849
1911	2376	80	38	1	2496	.	2496
1912	1433	34	26	.	1493	.	1493
1913	1601	37	20	.	1658	.	1658
1914	443	22	15	.	480	.	480
1915	1550	18	20	.	1588	.	1588
1916	957	8	39	.	1004	.	1004
1917	1264	5	77	.	1346	.	1346
1918	984	19	60	.	1062	.	1062
1919	1620	10	30	.	1660	.	1660
1920	1198	7	12	.	1217	.	1217
1921	1565	10	29	.	1604	.	1604
1922	1474	9	78	.	1561	.	1561
1923	975	7	16	.	999	.	999
1924	1392	6	37	.	1436	.	1436
1925	1029	7	69	1	1106	.	1106
1926	1205	10	46	.	1261	.	1261
1927	1400	5	43	.	1448	.	1448
1928	1309	3	64	.	1377	.	1377
1929	1573	10	37	.	1621	.	1621
1930	1385	5	23	.	1413	.	1413
1931	1421	34	14	.	1469	.	1469
1932	1153	7	110	.	1270	.	1270
1933	1417	7	101	.	1525	.	1525
1934	1232	8	54	.	1294	.	1294
1935	1475	4	55	.	1534	.	1534
1936	1577	5	71	.	1654	.	1654
1937	1590	3	102	.	1695	.	1695
1938	2009	4	136	.	2149	.	2149
1939	2415	5	159	.	2579	.	2579
1940	964	7	109	.	1080	.	1080
1941	903	5	118	.	1025	.	1025
1942	536	3	43	.	583	.	583
1943	588	1	29	.	618	.	618
1944	652	3	86	.	741	.	741
1945	597	8	82	.	687	.	687
1946	695	6	45	.	746	.	746
1947	836	5	27	2	870	.	870
1948	993	1	34	.	1028	.	1028
1949	1870	4	39	.	1913	.	1913
1950	5122	0	52	.	5174	.	5174

Table 1. (Continued)

Year	NS	NB	QC	PEI	SA 4	SA 3	Total
1951	3475	6	36	.	3518	.	3518
1952	.	.	.	.	1835	811	2646
1953	.	.	.	.	2122	651	2772
1954	.	.	.	.	1854	1252	3106
1955	.	.	.	.	1804	926	2730
1956	.	.	.	.	2301	1311	3612
1957	.	.	.	.	1249	2206	3455
1958	.	.	.	.	2550	2065	4615
1959	.	.	.	.	2518	2404	4922
1960	.	.	.	.	2665	2821	5486
1961	.	.	.	.	2358	2377	4735
1962	.	.	.	.	2326	1785	4111
1963	.	.	.	.	2070	1289	3359
1964	.	.	.	.	2166	1830	3996
1965	.	.	.	.	2302	1589	3891
1966	.	.	.	.	1788	1138	2926
1967	.	.	.	.	1708	6762	8470
1968	.	.	.	.	1661	8208	9869
1969	.	.	.	.	1547	597	2144
1970	.	.	.	.	1339	842	2181
1971	.	.	.	.	1459	843	2302
1972	.	.	.	.	1160	672	1832
1973	.	.	.	.	743	31	774
1974	.	.	.	.	1073	754	1827
1975	.	.	.	.	921	649	1570
1976	.	.	.	.	910	652	1562
1977	.	.	.	.	863	735	1598
1978	.	.	.	.	1227	430	1657
1979	.	.	.	.	1356	544	1900
1980	.	.	.	.	1660	414	2074
1981	.	.	.	.	1490	389	1879
1982	.	.	.	.	1816	660	2476
1983	.	.	.	.	2006	694	2700
1984	.	.	.	.	2170	1270	3440
1985	.	.	.	.	2119	2273	4392
1986	.	.	.	.	1946	2027	3973
1987	.	.	.	.	1444	1769	3213
1988	.	.	.	.	1504	1364	2868
1989	.	.	.	.	.	.	.
1990	.	.	.	.	1548	1500	3048
1991	.	.	.	.	1327	1932	3259

Sources: 1867-1916: Annual Report of the Dept. of Marine and Fisheries; 1917-1951: Fisheries Statistics of Canada; for 1867-1885: original values in barrels converted as 1 bbl = 200 lbs; for 1871-1946: Original values in hundredweights converted as 1 cwt = 112 lbs. for 1951 – 1978 ICNAF. 1979- 1991 NAFO

Table 2. Landings of Atlantic halibut caught in the Scotia Shelf and Southern Grand Banks stock (3NOPs4VWX5Zc).

	Canada					Foreign				
Year	Bottom OT	Longline	Other	Total		Bottom OT	Longline	Other	Total	Grand Total
1960	458	2508	178	3144		290	704		994	4138
1961	676	1940	117	2733		584	277		861	3594
1962	1189	1559	141	2889		438	134		572	3461
1963	679	1403	133	2215		333	34	31	398	2613
1964	741	923	290	1954		747	83	3	833	2787
1965	640	1138	116	1894		498	50	19	567	2461
1966	245	1150	63	1458		458	16	15	489	1947
1967	520	1398	72	1990		614	71	24	709	2699
1968	598	1071	107	1776		349	28	1	378	2154
1969	572	893	68	1533		345	52	1	398	1931
1970	649	852	48	1549		55	78	36	169	1718
1971	477	938	49	1464		155	57	33	245	1709
1972	355	842	67	1264		110	21	20	151	1415
1973	350	881	24	1255		52	17		69	1324
1974	253	705	57	1015		106	22	39	167	1182
1975	310	673	18	1001		81	25	24	130	1131
1976	327	654	29	1010		82	9	17	108	1118
1977	666	580	66	1312		20	4	27	51	1363
1978	536	757	176	1469		17	10	26	53	1522
1979	670	885	117	1672		17	3	51	71	1743
1980	602	1107	88	1797		50	3	22	75	1872
1981	483	1149	90	1722		37	2	30	69	1791
1982	749	1474	77	2300		35	3	53	91	2391
1983	413	1692	88	2193		11	19	190	220	2413
1984	419	2392	64	2875		93	1	143	237	3112
1985	901	2636	50	3587		265	29	215	509	4096
1986	705	2352	74	3131		181	9	54	244	3375
1987	289	1649	47	1985		607		4	611	2596
1988	173	1912	24	2109		197	67	16	280	2389
1989	133	1731	26	1890		99	5	13	117	2007
1990	245	1599	21	1865		374	21		395	2260
1991	271	1158	19	1448		661		135	796	2244
1992	162	1158	28	1348		105		2	107	1455
1993	183	1039	37	1259		63		2	65	1324
1994	44	982	37	1063		89	1	1	91	1154
1995	61	659	31	751		72		3	75	826
1996	47	711	51	809		41		1	42	851
1997	54	844	134	1032		55			55	1087
1998	34	799	108	941		74			74	1015
1999	36	771	63	870		139			139	1009
2000	12	790	55	857		87			87	944
2001	50	1133	90	1273		140			140	1413
2002	60	1086	136	1282		178			178	1460
2003[1]	96	1404	134	1633	180		1	320	1814	1815

Table 2. (Continued)

2004	93	1156	78	1327	110	1	111	1438	1440
2005	84	1104	81	1269	46		46	1315	1317
2006	60	1216	82	1358	20	0	20	1378	1378
2007	88	1378	34	1500	30		30	1530	1534
2008[2]	74	1300	60	1433	25		25	1458	1458
2009[2]	105	1855	85	2045	36		36	2081	2081

[1]Breakdown of total landing into categories was estimated from the mean proportion in each category for 2002 and 2004.

[2]Breakdown of total landing into categories was estimated from the mean proportion in each category for 2006 and 2007.

Note: Landings were taken from NAFO statistics and are for the calendar year.

Table 3. Reported ages and lengths at maturity for Atlantic halibut (Hippoglossus hippoglossus).

Area	Age at 50% maturity,yr	Fork length at 50% maturity,cm	Reference
Gulf of St. Lawrence		130 ♀	DFO 2009a CSAS 2009/023
		115 ♀ 75 ♂	DFO 2007 CSAS 2007/007
Scotian Shelf and Grand Bank		100 ♀ 66-70 ♂	Kohler 1967
SA 4	10-12 ♀ 8-11♂	110-119 ♀ 80♂	McCracken 1958
Gulf of Maine-Georges Bank	7.3 ♀ 6 ♂	103 ♀ 80 ♂	Sigourney 2006
Newfoundland	12 ♀ 8 ♂	119 ♀ 77 ♂	Trumble et al. 1993
Grand Banks		115-120♀ 80 ♂	Methven et al. 1992
Newfoundland and Labrador (1972-1984)	12 ♀ 8 ♂	125 ♀ 80 ♂	Bowering, 1986
Western North Atlantic	7-12 ♀	105-150♀	Miller et al. 1991
Iceland	>9 or 10 ♀ or ♂		Jespersen 1917
Faroese (1986-1986)	7 ♀ 4.5 ♂	110-115 (18kg) ♀ 55 (1.7kg) ♂	Jákupsstovu and Haug 1988
Northern Norway (1936-1938)	13 ♀ 12 ♂		Haug and Tjemsland 1986
Northern Norway (1955-1960)	8-18 ♀ 7-17 ♂		Devold 1938

Table 4. Cross tabulation of release and recapture by NAFO division Atlantic halibut tagged as part of the most recent (2006-2008) DFO-Industry tagging program in 3NOPs4VWX. (n=2064, release period of 12 days to 4 years).

Release	Total	Return Area										Total
Area	**Released**	**3N**	**3O**	**3P**	**4R**	**4T**	**4V**	**4W**	**4X**	**5Y**	**Unknown**	**Recaptured**
3N	201	5	44	2					2		4	57
3O	147		5	7	1						1	14
3P	410	1	8	63			10		2		6	90
4V	554		1	10	2	6	85	10			9	123
4W	463			3			4	35	6		13	61
4X	289			5			3	10	40	3	5	66
Total	2064	6	58	90	3	6	102	55	50	3	38	411

Table 5. Cross tabulation of release and recapture by NAFO division of Atlantic halibut tagged by commercial fishermen in the Gulf of St. Lawrence (4RST) and 3Pn between 1998 and 2008 (Diane Archambault, pers. comm.). The time between release and recapture events was between one day and 9 years.

		Return Area							
Release Area	**Total Released**	**3Pn**	**3Ps**	**4R**	**4S**	**4T**	**4Vn**	**Unknown**	**Total Recaptured**
3Pn	213	17	0	5	0	0	1	0	23
4R	5984	5	0	147	31	0	0	7	190
4S	127	0	0	0	12	0	0	0	12
4T	997	5	2	2	7	55	16	1	88
Total	7321	27	2	154	50	55	17	9	313

Table 6. Time line of changes to halibut fishery data.

Year	Description
1867 - 1950	Landings recorded by province by Statistics branch
1951 – present	Landings recorded by ICNAF then by NAFO
1948	Groundfish port sampling started, but halibut not measured because fish were landed with heads off.
1977 – present	Observers on board otter trawl fleet
1988 – present	Observers on board longline fleet
1989	First halibut port samples recorded
1994	Legal limit of ≥81cm
1998 – present	Halibut survey started. Associated commercial index provides many samples with which to estimate commercial catch at length

Table 7. Equations for the halibut population assessment model.

Population dynamics

(1) $$C_{t,s} = \frac{F_{t,s} N_{t,s} (1 - \exp(-Z))}{Z}$$

(2) $$N_{t+1,s,a+1} = N_{t,s,a} \exp(-(M + F_{t,s,a}))$$

(3) $$F^{i}_{t,s,a} = s^{i,s}_{a} F^{i}_{t}$$

(4) $$SSB_{t,F} = N_{t,F,a} m_{F,a} w_{F,a} /1000$$

LL survey and fishery (*i*) selectivity:

(5) $$s^{i,s}_{a} = \frac{1}{1 + \exp\left(-\gamma(a - \delta)\right)}$$

RV surveys and OT fishery (*i*) selectivity:

(6) $$s^{i}_{a} = \left\{ \begin{array}{ll} \exp\left(\dfrac{-(a - s^{i}_{full})^2}{v^{i}_{L}}\right) & \text{if } \ a \le s^{i}_{full} \\ \exp\left(\dfrac{-(a - s^{i}_{full})^2}{v^{i}_{R}}\right) & \text{if } \ a \le s^{i}_{full} \end{array} \right\}$$

Abundance indices (*i*): NS RV survey, halibut survey, commercial index

(7) $$I^{i}_{t} = q^{i} \sum_{s,a} \exp(-hM)(1 - h\mu^{i}_{t,s,a}) s^{i,s}_{a} N_{t,s,a} ,$$ where $h = 0.5$

Sex specific predicted length composition in the catch

(8) $$P_{t,l}^{i,s} = \frac{\sum_a s_a^{i,s} f_{l|a}^{s} N_{t,s,a}}{\sum_a s_a^{i,s} \sum_a f_{l|a}^{s} N_{t,s,a}}$$

Sex-specific length proportion-at-age

(9) $$f_{l|a}^{s}(l_a^s, \sigma_a^s) = \frac{\delta}{\sqrt{2\pi}\sigma_a^s} \exp\left[\frac{-(x_l^s - l_a^s)^2}{2(\sigma_a^s)^2}\right]$$

Log likelihoods for each survey (*k*)

(10) $$\ell_{index}^{k} = -n \ln \sigma_k \sqrt{2\pi} - \sum_t I_t - \frac{1}{2\sigma_k^2} \sum_t (\ln I_t - \ln \hat{I}_t)^2$$

Multinomial likelihood for length frequency data

(11) $$\ell_{LF}^{k} = -\sum_i (NO_i) * \log(E_i + 1\text{e}^{-6}) + \sum_i (NO_i) * \log(O_i + 1\text{e}^{-6}),$$

where *O* = observations, *E* = fitted values and *N* the effective sample size

Constraint on recruitment

(12) $$penality = \sum_t (\log(N_{t,s,1} / N_{t+1,s,1}) / \sigma^2)^2 * 0.5$$

Objective function value (ofv)

(13) $$ofv = \ell_{LF}^{k} + \ell_{index}^{k} + penalities$$

Table 8. Data used to fit population dynamics mode of Atlantic halibut. The length composition data for the longline (LL) fishery was separated by sex. Sigma's are assumed.

Data component	Years of data	Likelihood form	σ or sample size
FISHERY DATA			
Canadian landings (LL and OT)	1970-2009	None	None
Foreign landings (OT)	1970-2009	None	None
Catch length composition (LL)	1988-2009	Multinomial	$n_t \leq 150$
Catch length composition (OT)	1984-2009	Multinomial	$n_t \leq 150$
ABUNDANCE INDICES			
Total numbers caught			
NS RV summer survey (4VWX)	1970-2009	Lognormal	$\sigma = 0.1$
Standardized catch rate			
Halibut survey	1998-2009	Lognormal	$\sigma = 0.1$
Length composition			
NS RV summer survey (4VWX)	1970-2009	Multinomial	$n_t \leq 150$
Halibut survey	1998-2009	Multinomial	$n_t \leq 150$
SEX RATIO			
Halibut survey	1998-2009	Lognormal	$\sigma = 0.1$

Table 9. Penalties or constraint

Penalties	Objective	Form
Fishing mortality	Keep below 1.0	Posfun
Constraint		
Recruitment	Reduce annual variance in recruitment	Random walk, lognormal error σ = 0.5

Table 10. Parameter estimates and state variables (F, SSB) using maximum likelihood (MLE) and the asymptotic normal standard error (SE). Parameters without an SE indicates that it was fixed and not estimated. The MLE and the Bayesian posteriors are plotted in Appendix D.

	Symbol	Period	MLE	SE
SELECTIVITY PARAMETERS				
Shape parameter				
Otter trawl fishery	v_L^i	1977-2009	1.2	
Otter trawl fishery	v_R^i	1977-2009	20.0	
NS RV summer survey	v_L^i	1970-2009	0.1	
NS RV summer survey	v_R^i	1970-2009	6.42	3.1×10^{-1}
Longline fishery	γ_{male}	1988-2009	7.0	
Longline fishery	γ_{female}	1988-2009	7.0	
Halibut survey	γ_{male}	1998-2009	7.0	
Halibut survey	γ_{female}	1998-2009	7.0	
50% retention				
Otter trawl fishery	s_{full}^i	1977-2009	5.00	
NS RV summer survey	s_{full}^i	1970-2009	2.80	5.8×10^{-2}
Longline fishery	δ_{male}	1988-2009	5.47	2.8×10^{-2}
Longline fishery	δ_{female}	1988-2009	5.88	2.5×10^{-2}
Halibut survey	δ_{male}	1998-2009	5.55	3.7×10^{-2}
Halibut survey	δ_{female}	1998-2009	5.51	5.0×10^{-2}
CATCHABILITY COEFFICIENTS	q^i			
NS RV summer survey		1970-2009	8.78×10^{-1}	1.7×10^{-2}
Halibut survey		1998-2009	-1.74	4.1×10^{-2}
INITIALIZATION PARAMETERS				
Starting recruitment (age-1)	N_1	1970	1.49×10^5	2.6×10^3
Total mortality in first year used to estimate ages 2 to 20	Z_{1970}	1970	0.2	
MORTALITY PARAMETERS				
Fishing mortality (males)	F	2009	0.14	3.3×10^{-3}
Fishing mortality (females)	F	2009	0.31	8.8×10^{-3}
Natural mortality	M	1970-2009	0.1	
Spawning stock biomass	SSB	2009	6527	170

Table 11. Contribution of each data set to the overall fit of the model.

Data component	Proportion of total likelihood
FISHERY DATA	
Catch length composition	0.29
ABUNDANCE INDICES	
NS RV summer survey	0.41
Halibut survey	0.01
LENGTH COMPOSITION ALL SURVEYS	0.29
NS RV summer survey	
Halibut survey	

Table 12. Comparisons between the catch at length model (CAL; used in this assessment), the statistical catch-at-age (CAA) model and virtual population analysis (VPA).

Model Type	Number of parameters	Fitting time step	SSB_{2009} (t)	F_{2009}
CAL	46	Forward	6527	0.14 males
				0.30 females
CAA	88	Forward	5280	0.17
VPA	10	Backward	5790	0.18

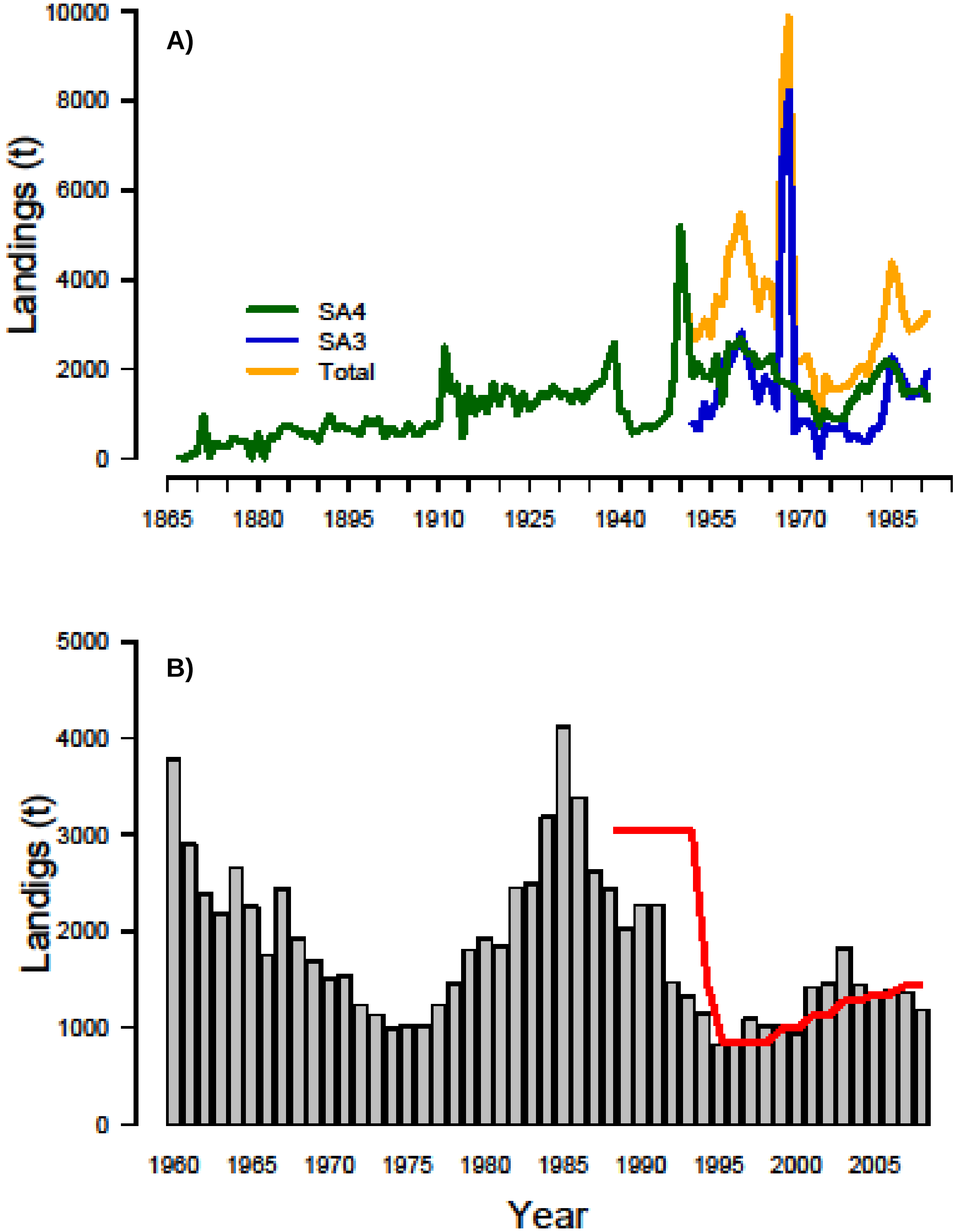


Figure 1. A) Atlantic halibut landings in Nova Scotia, New Brunswick, Prince Edward Island, and Quebec (SA4) and Newfoundland (SA3). B) Atlantic halibut landings in NAFO Divs. 3NOPs4VWX and Total Allowable Catch (TAC) in red.

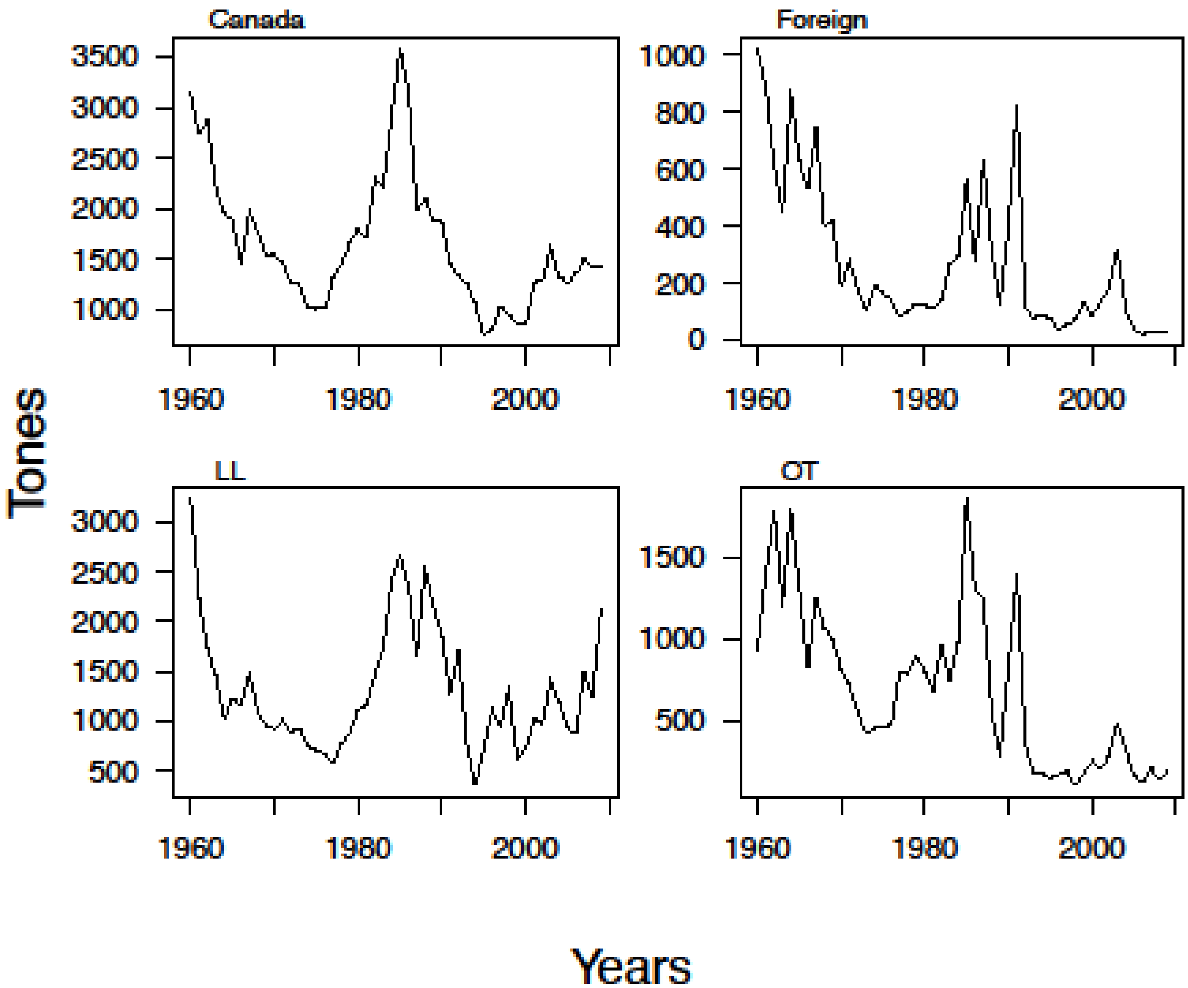


Figure 2. Atlantic halibut total catch (including discards since 1994) by Canadian and foreign fishing fleets by longline (LL) and otter trawl (OT) gear.

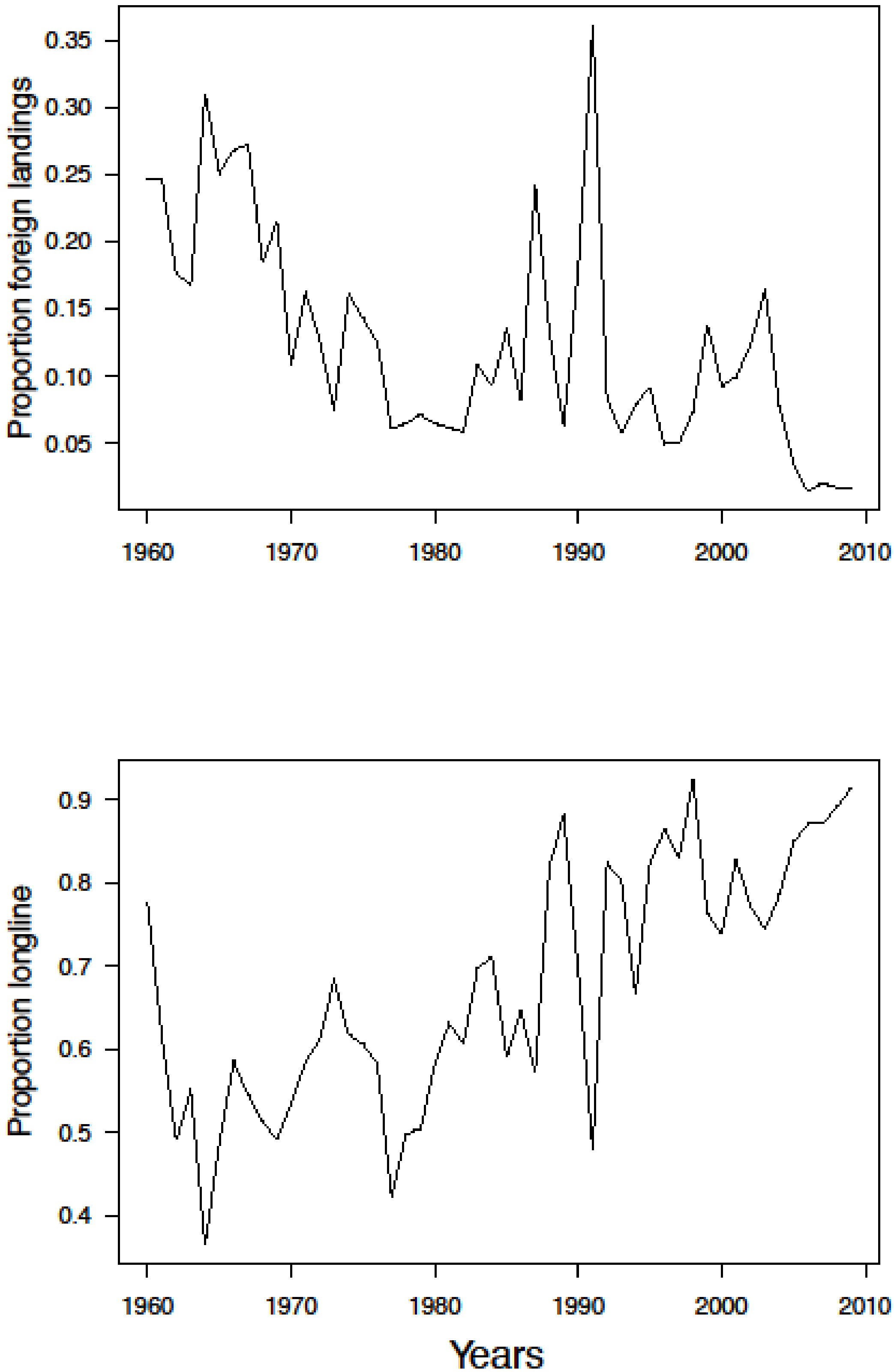


Figure 3. Proportion of landings caught by a) the foreign fishing fleet and b) longline gear.

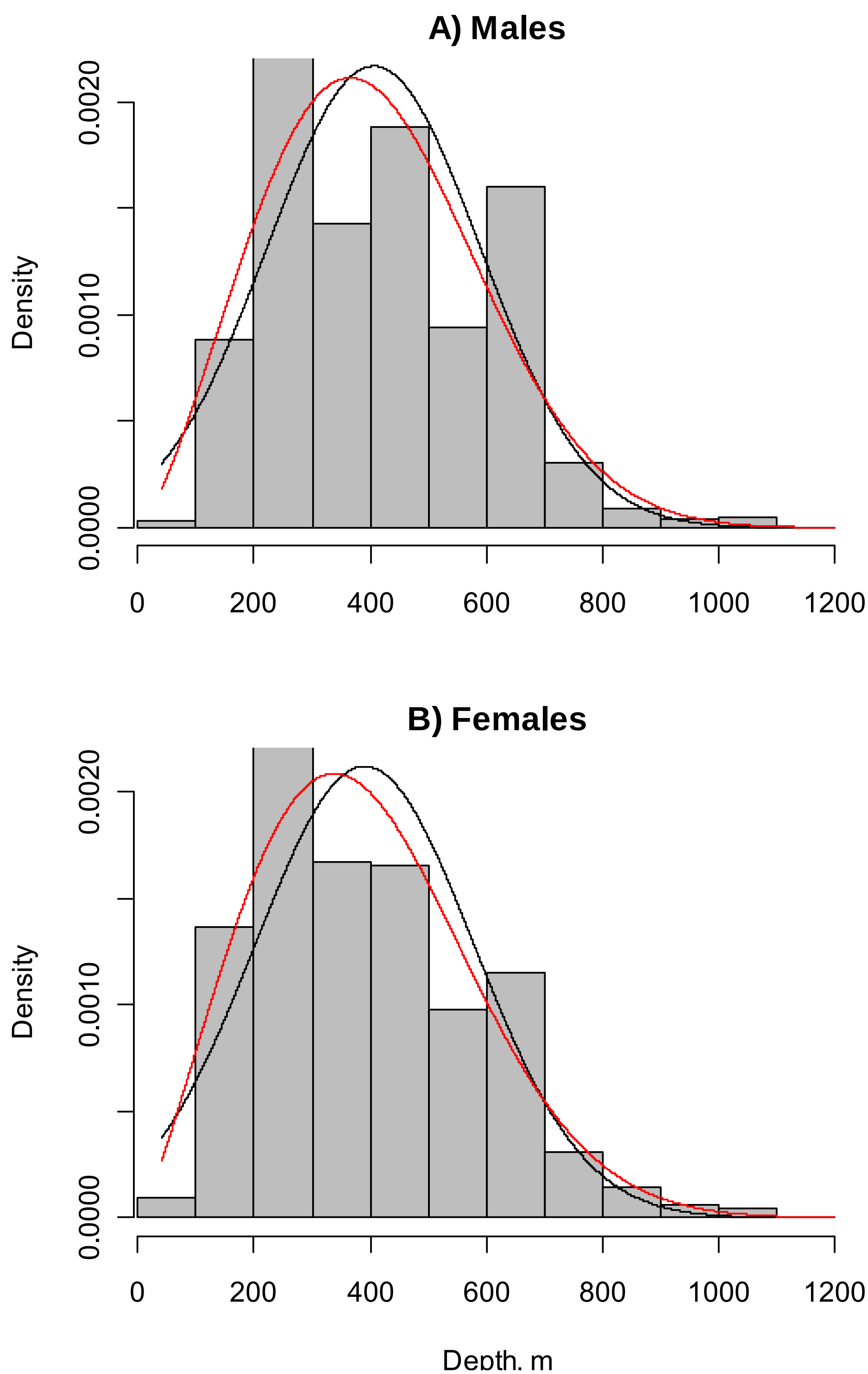


Figure 4. Density distribution of depths for A) males and B) females. The black line was the Gaussian fit to the distributions. The red line was a Weibull fit with WinBugs.

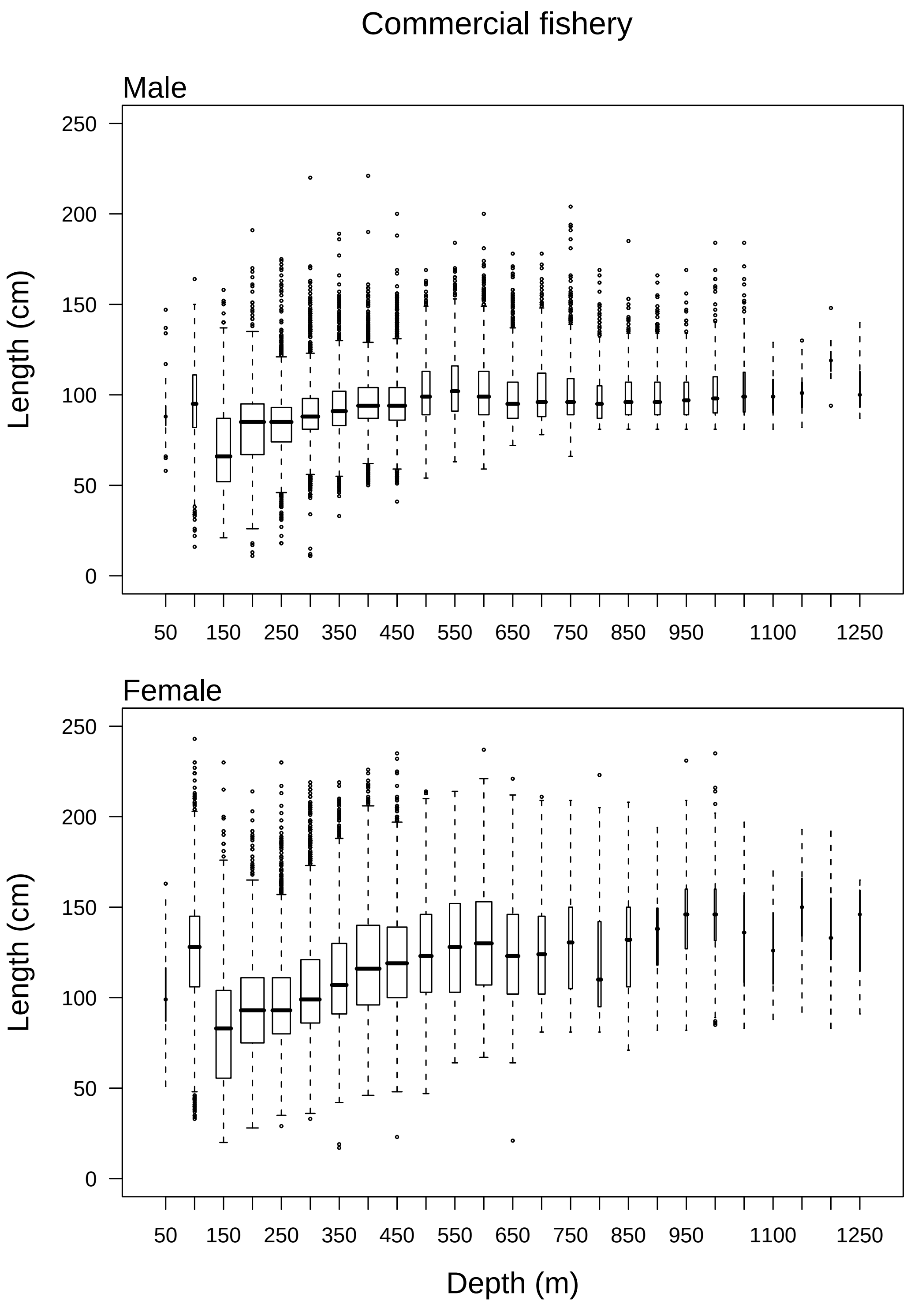


Figure 5. Length of males and females caught at depth in the commercial fishery (1977-2007). N = 5402 males, N = 4766 females.

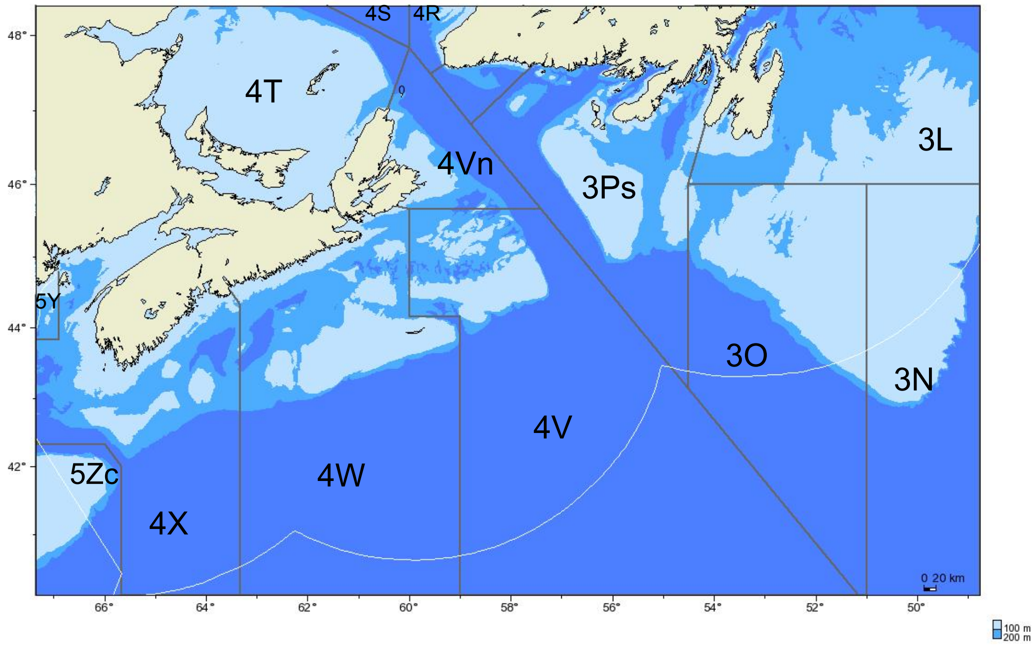


Figure 6. Map of the management unit (NAFO 3NOPs4VWX5Zc) for Atlantic halibut. The Gulf of St. Lawrence (4RST), the northern Grand Banks (3L), and US waters are outside the management unit. The white line indicates the Exclusive Economic Zone (EEZ).

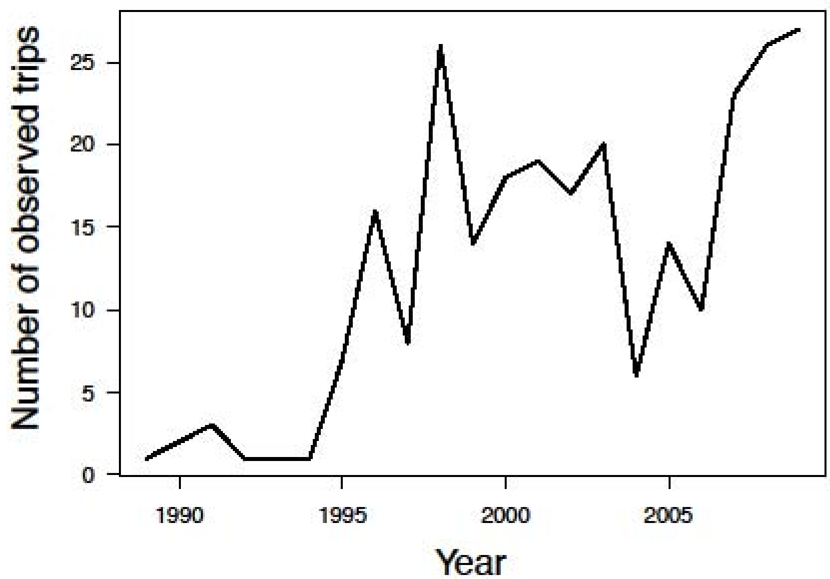


Figure 7. The annual number of observed halibut longline fishing trips.

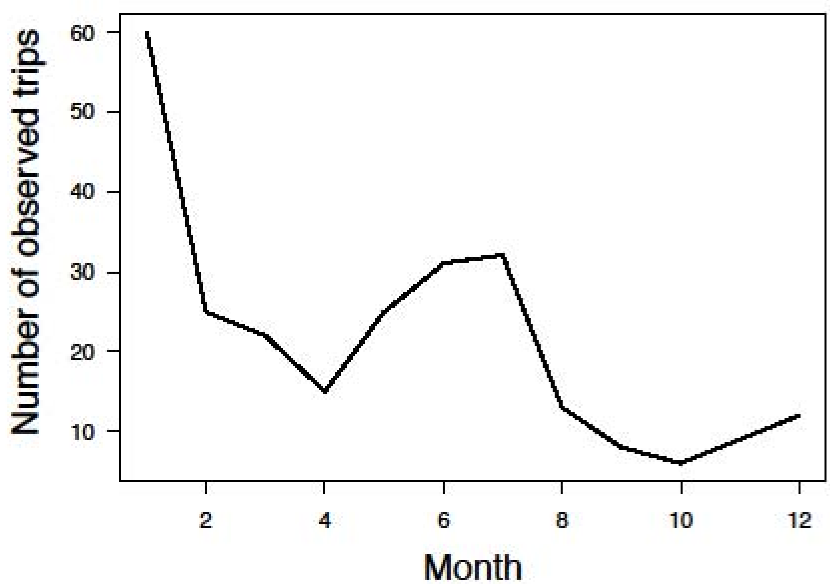


Figure 8. Number of observed halibut longline fishing trips by month.

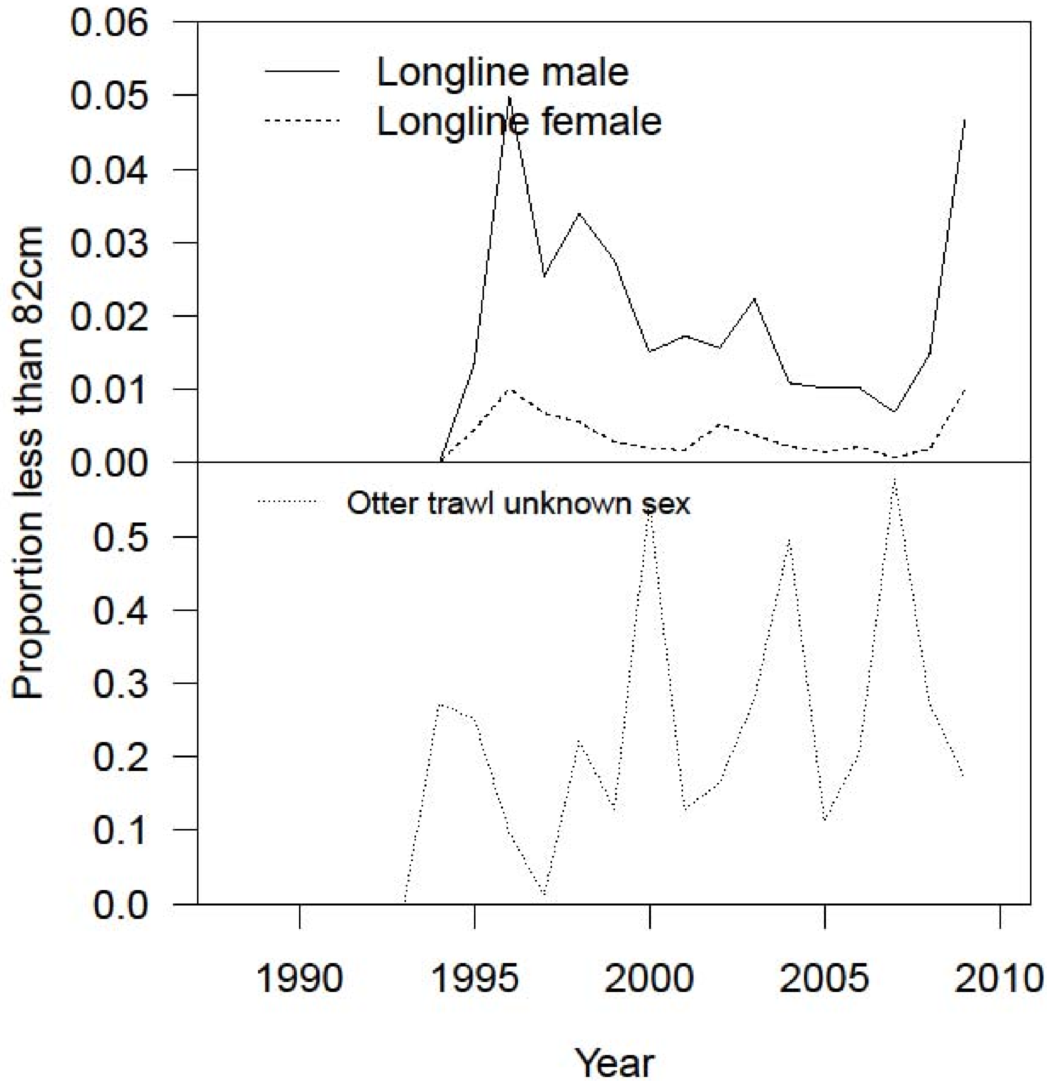


Figure 9. The proportion of the observed catch less than 82cm in the longline and otter trawl fishery.

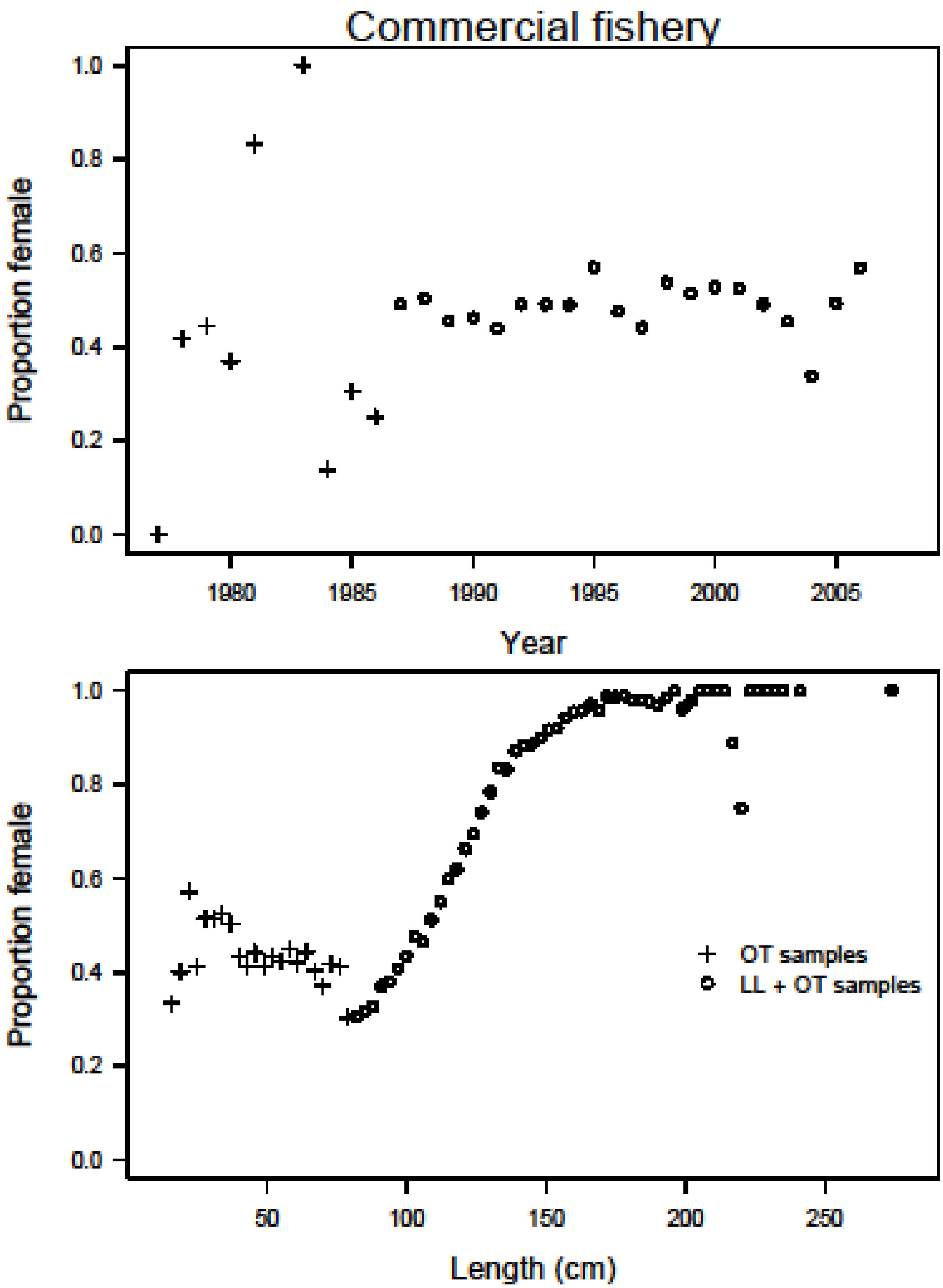


Figure 10. Proportion female in the commercial fishery by year, and length.

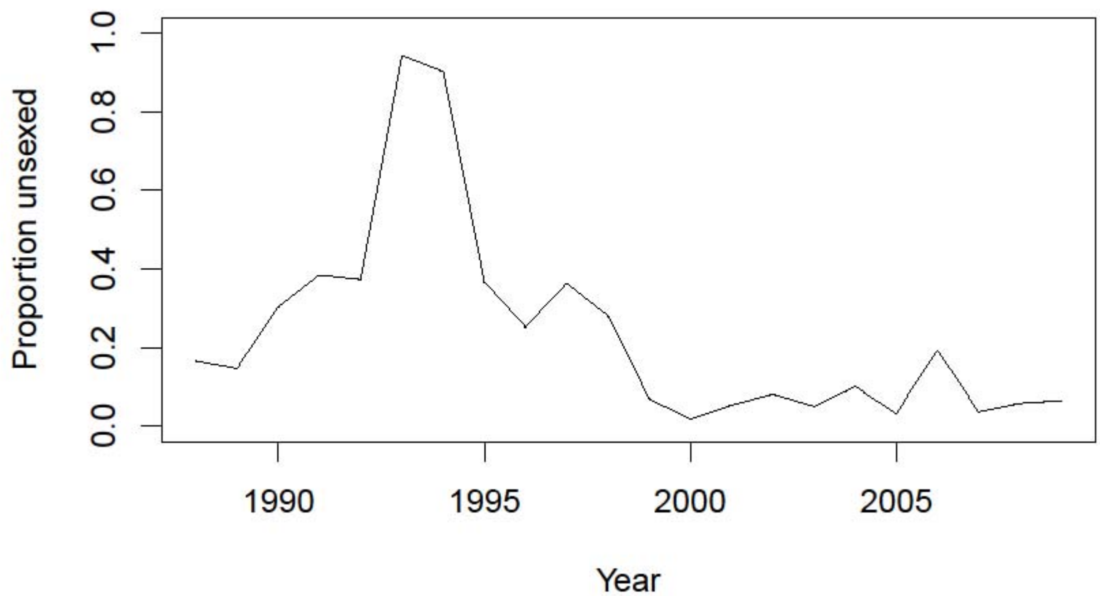


Figure 11. The proportion of fish that were unsexed in observed longline trips.

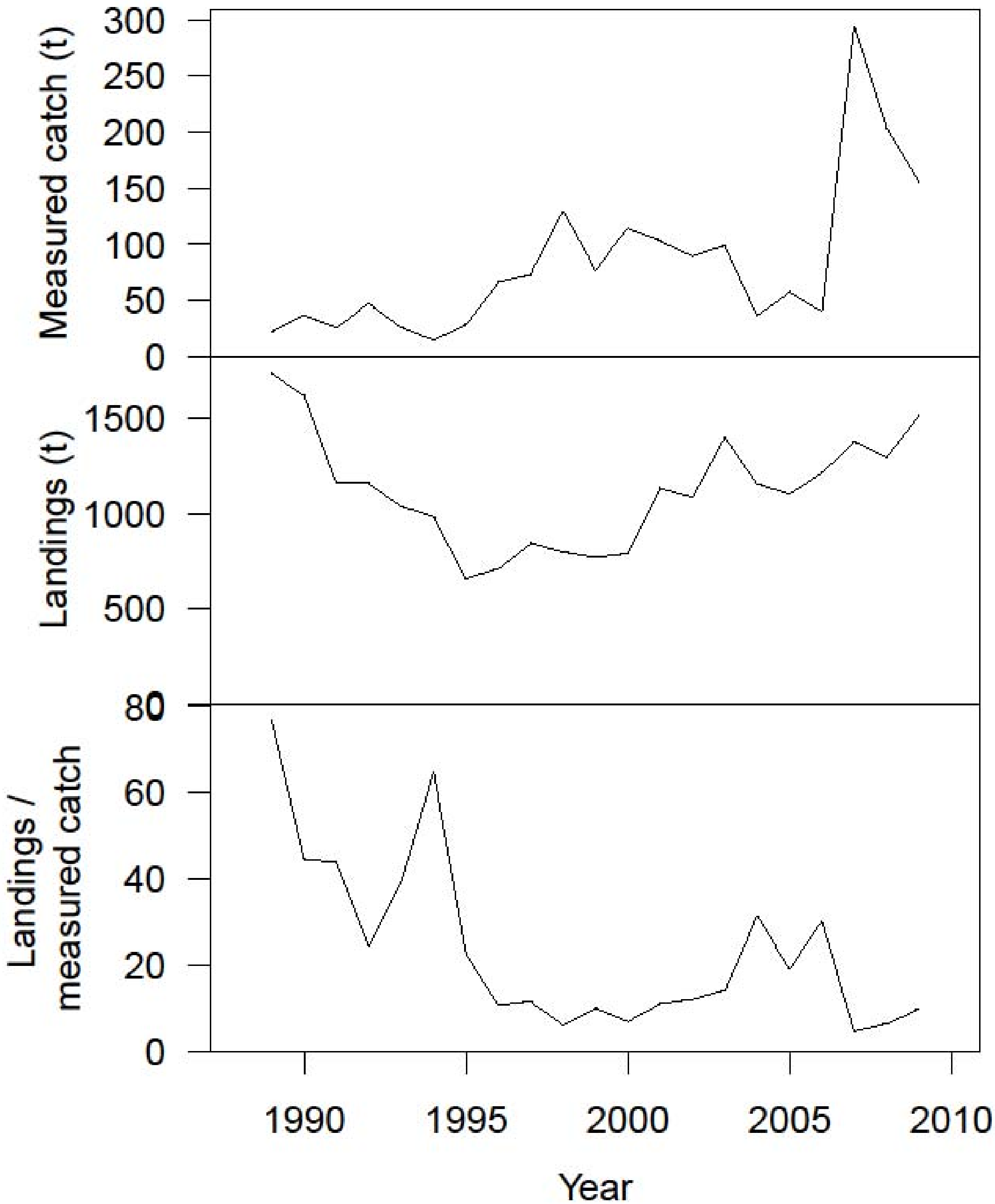


Figure 12. The measured catch (observer + port samples), landings, and bump-up factors for the longline fishery.

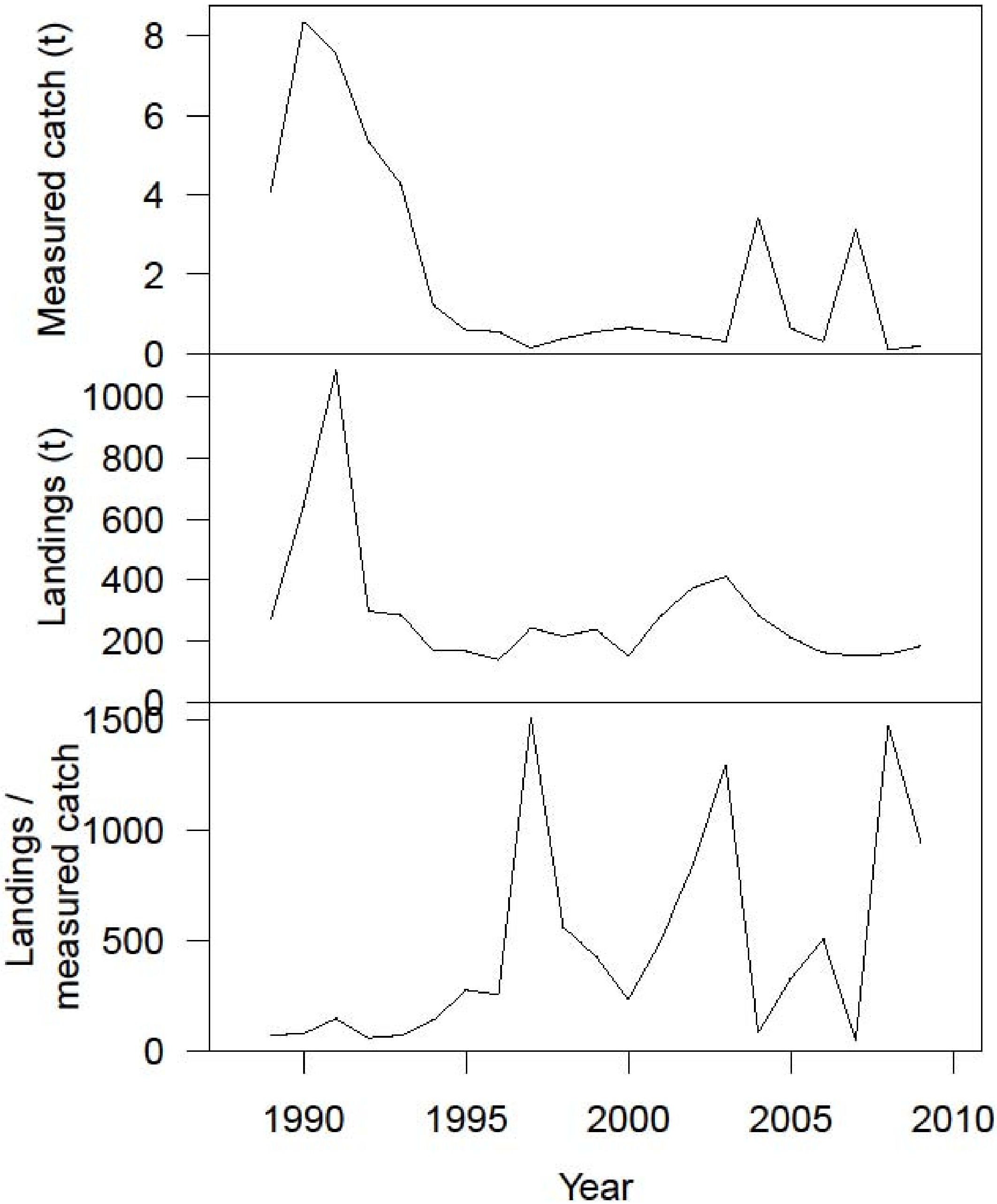


Figure 13. The measured catch (observer + port samples), landings, and bump-up factors for the otter trawl fishery.

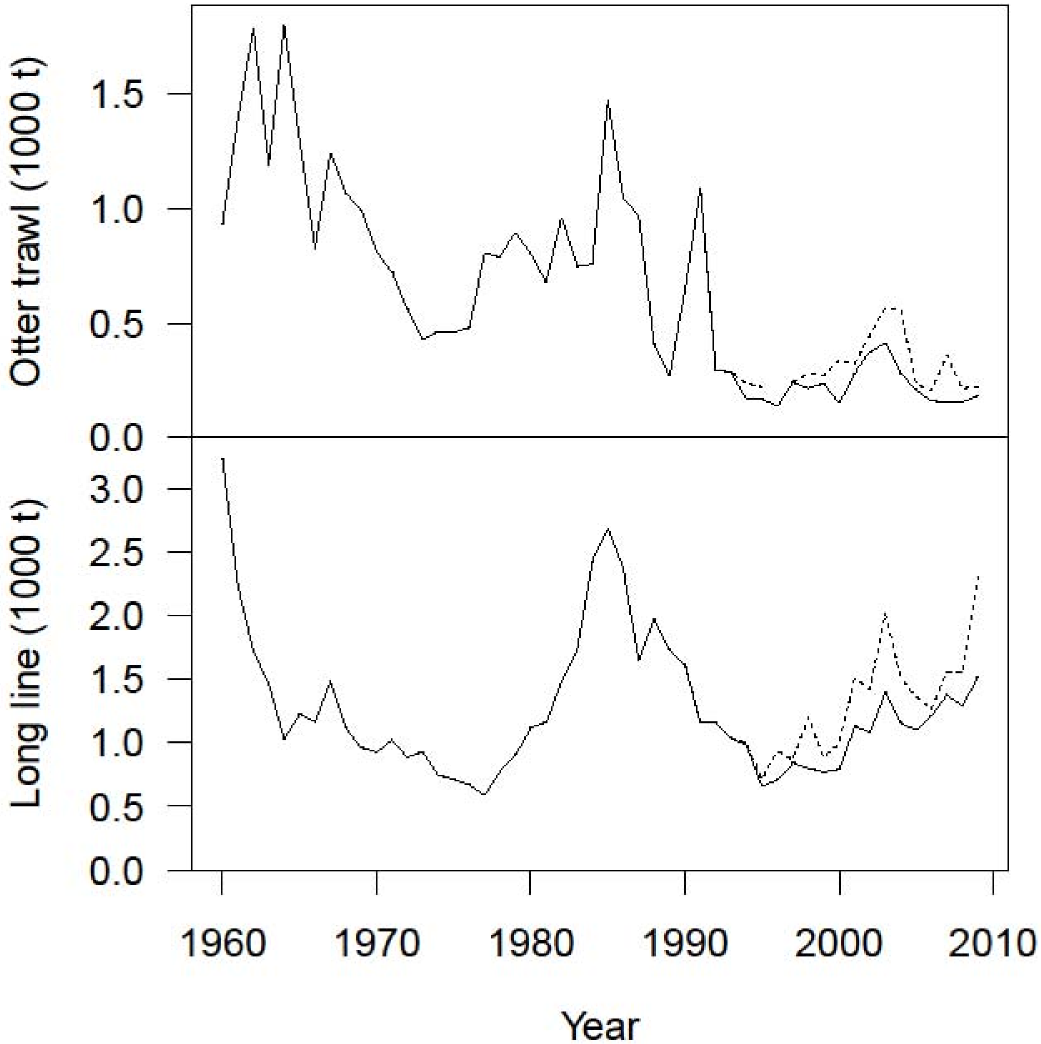


Figure 14. The Atlantic halibut landings and estimated total catch in the otter trawl and longline fishery.

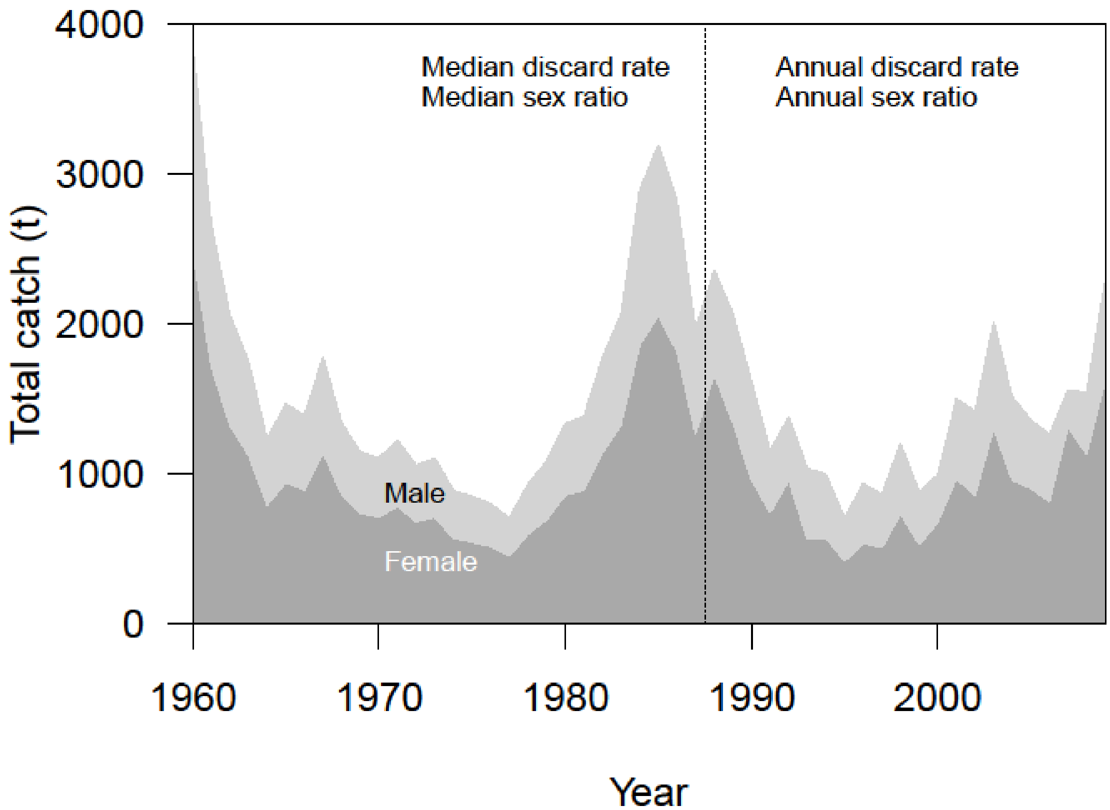


Figure 15. The Atlantic halibut estimated total catch of males and females in the longline fishery.

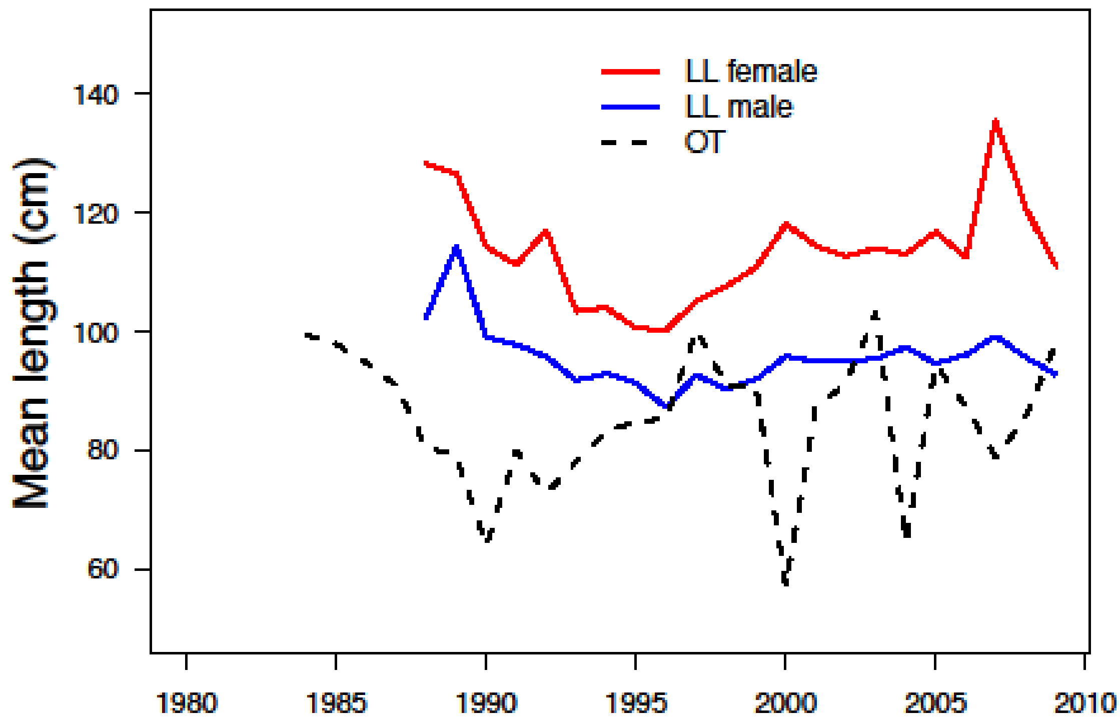


Figure 16. Mean lengths of male and female halibut caught in the longline (LL) fishery and for sexes combined in the otter trawl (OT) fishery.

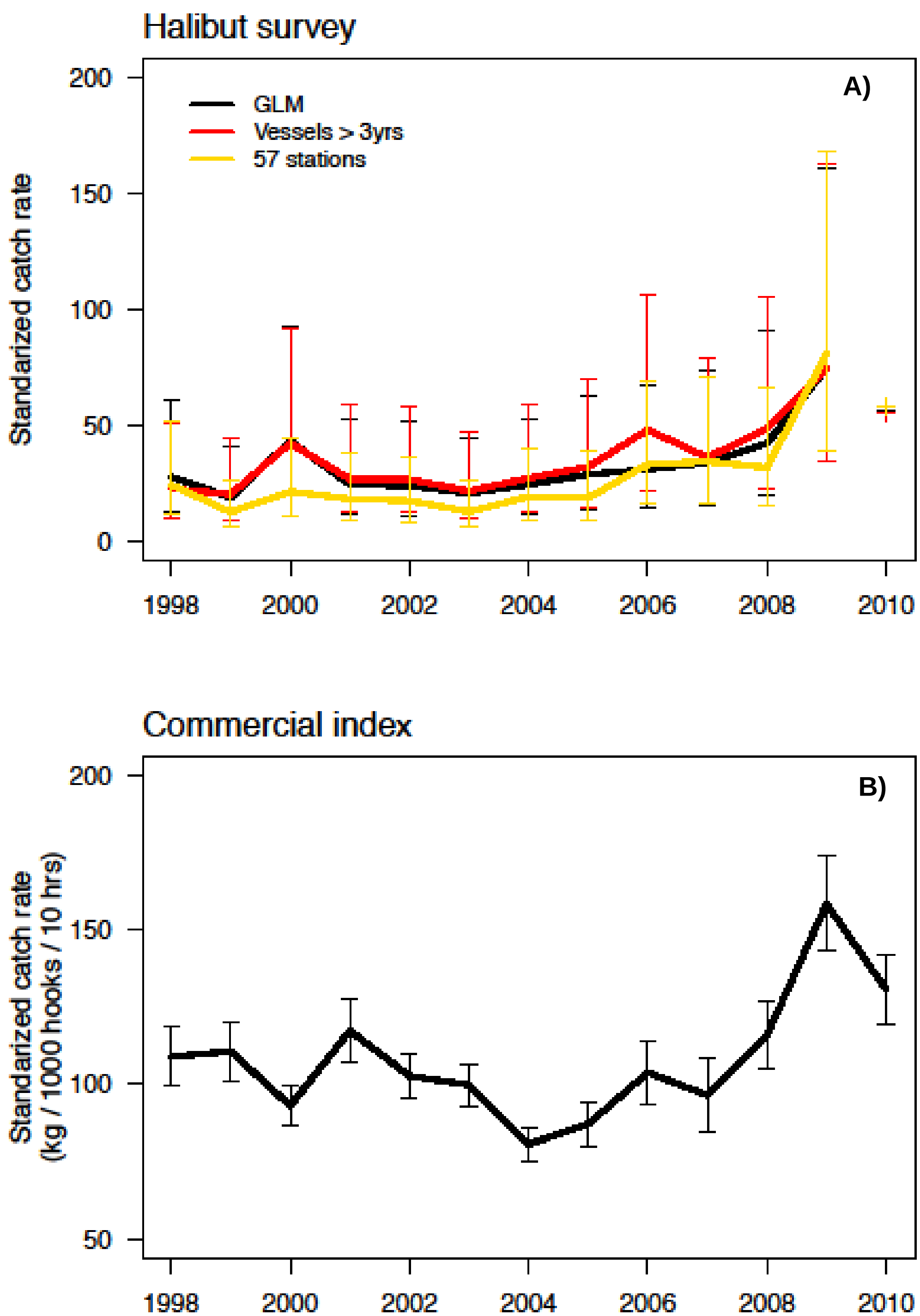


Figure 17. A) The standardized catch rate in the halibut survey using three approaches: a generalized linear model (GLM) of all stations covered 5 years or more, where vessels participated in > 3 years, and for 57 stations covered every year since 1999. The model was not fit to the 2010 point (+), but was shown for comparison. B) Trends in the commercial index catch rates. Error bars are ±2SE.

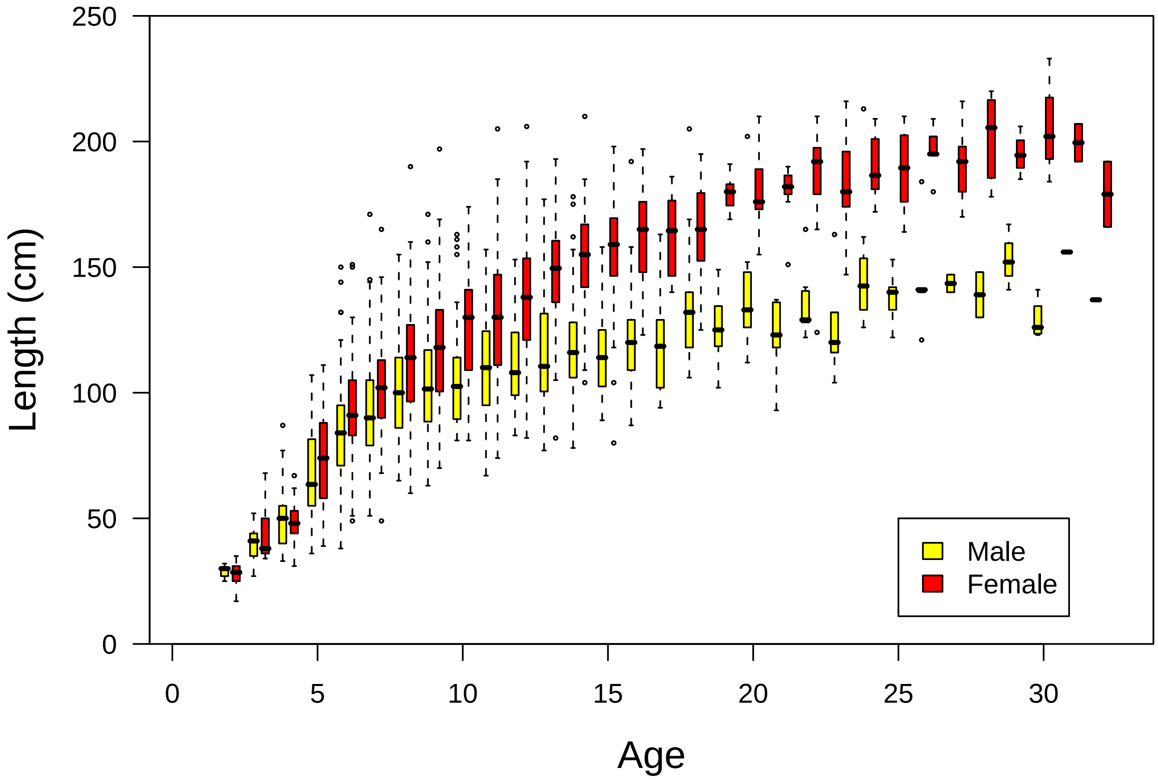


Figure 18. Length at age for male and female Atlantic halibut.

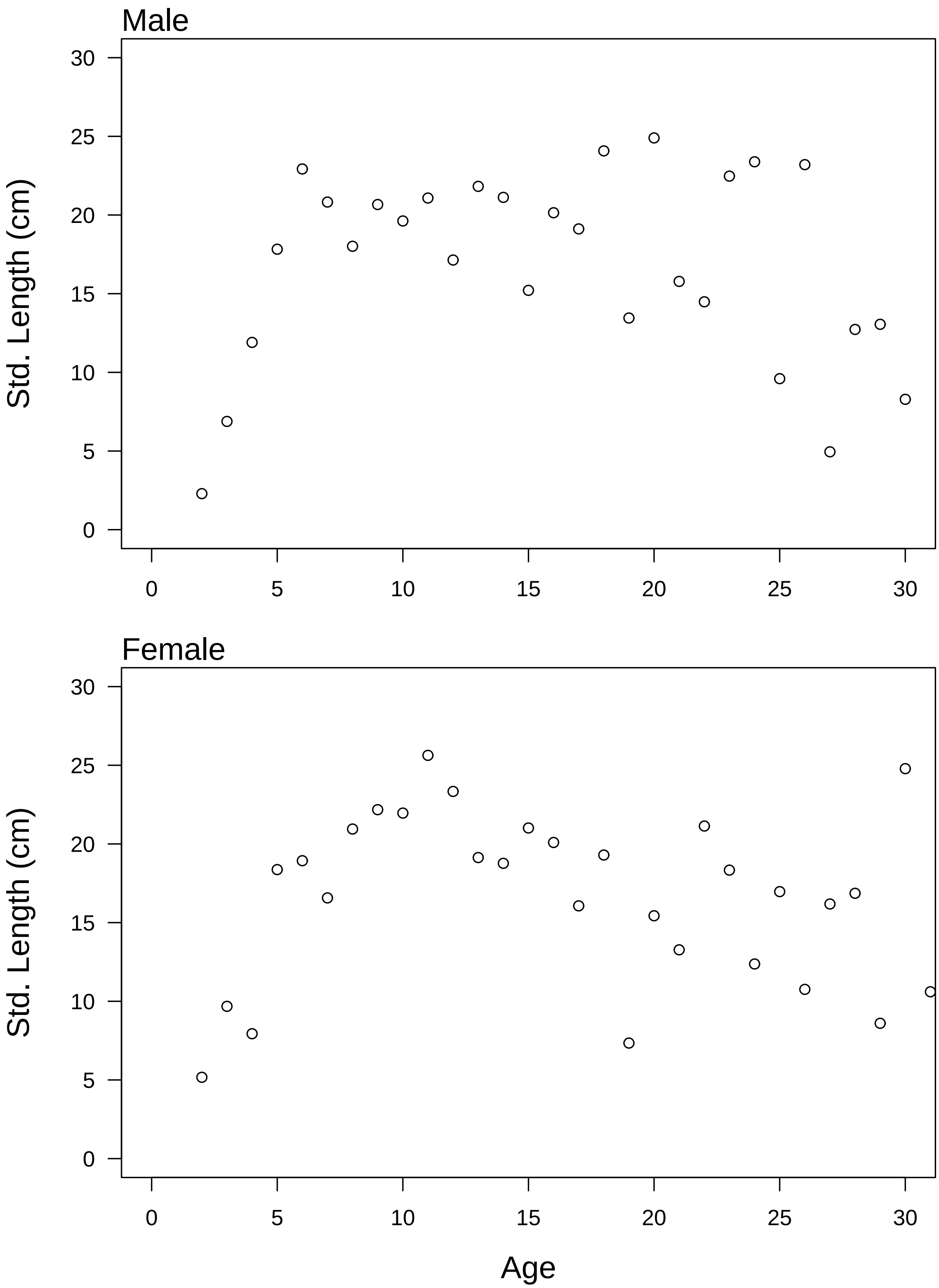


Figure 19. Standard deviation of length at age for male and female Atlantic halibut.

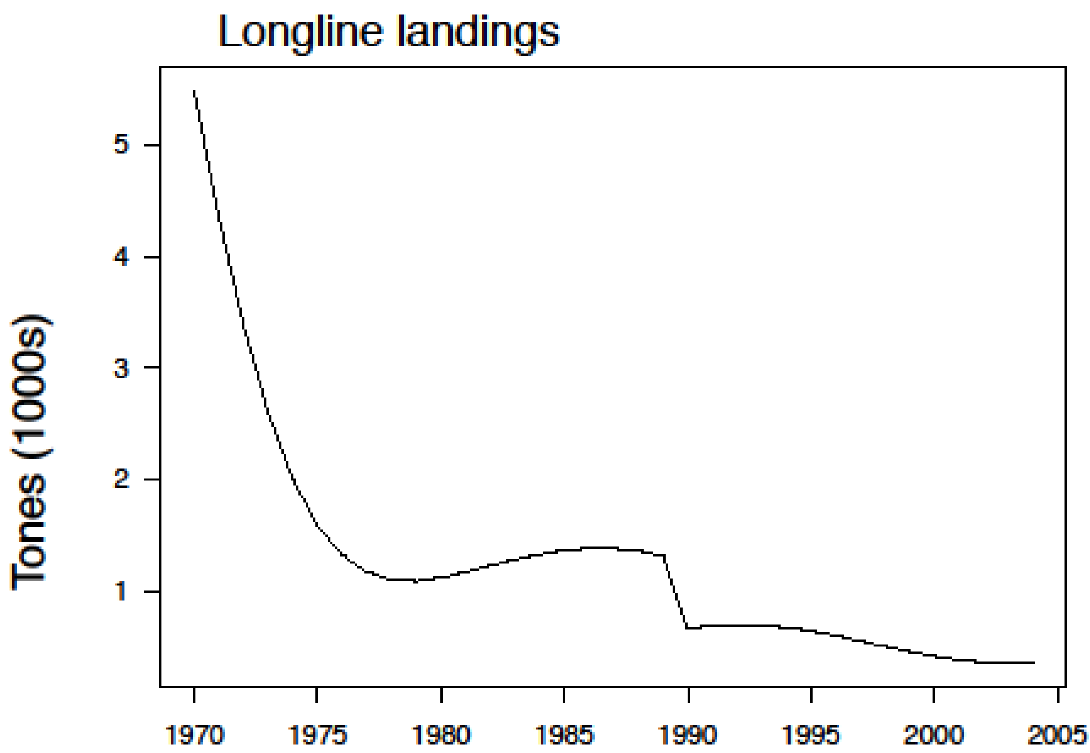


Figure 20. Simulated longline landings used for model testing.

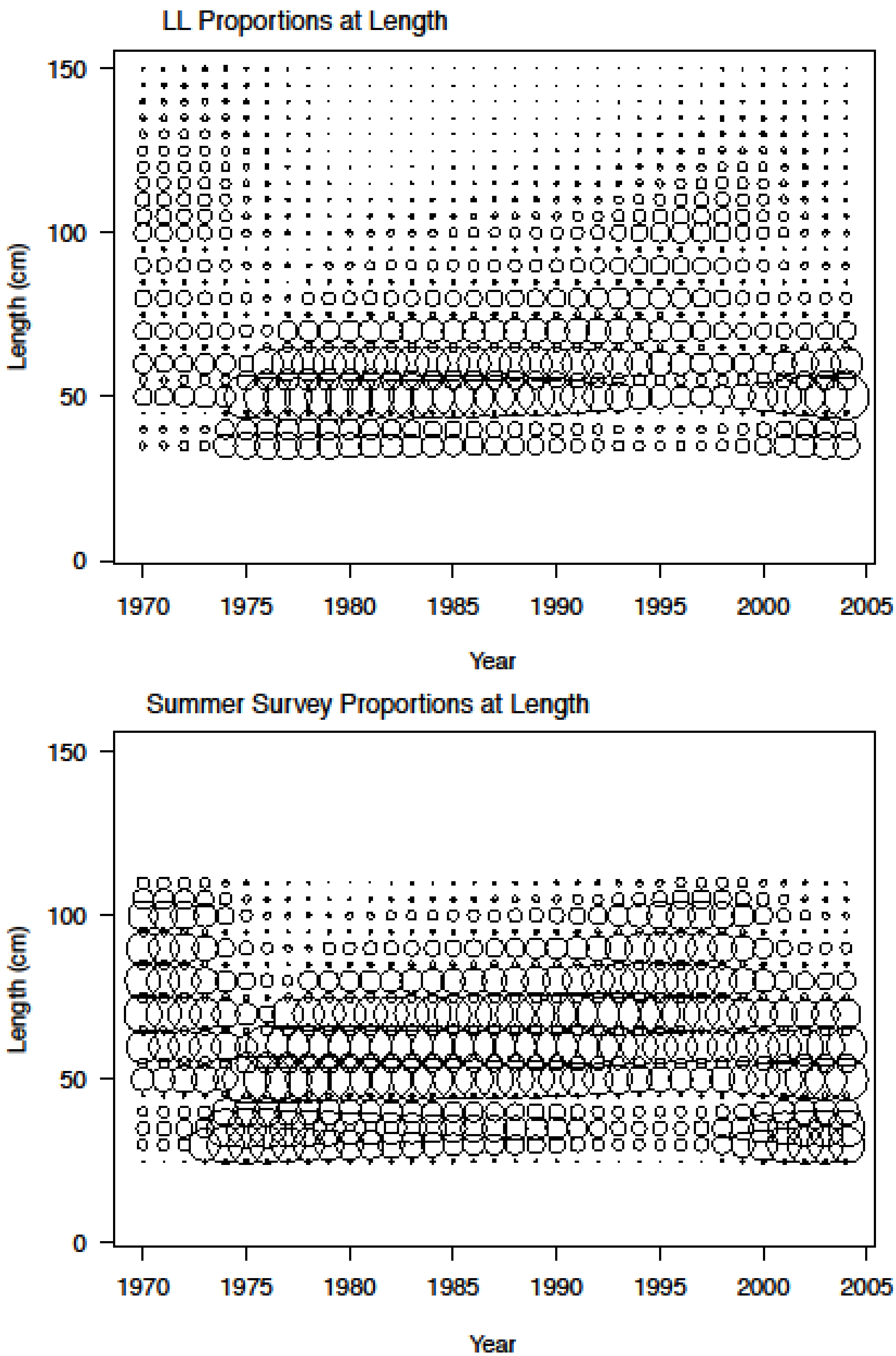


Figure 21. Simulated longline (LL) and RV survey proportions at length used for model testing.

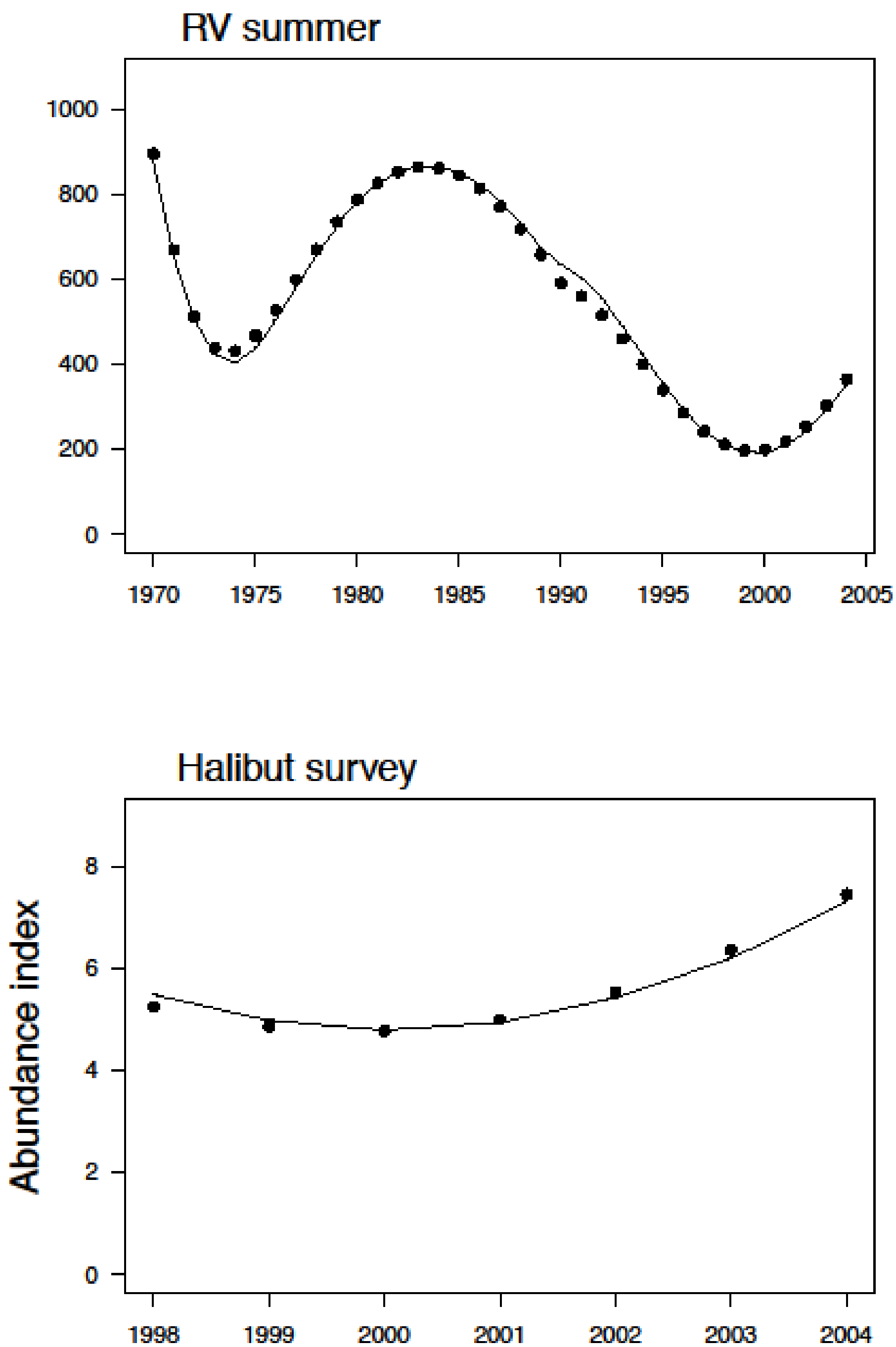


Figure 22. Simulated RV summer and halibut survey abundance indices used for model testing.

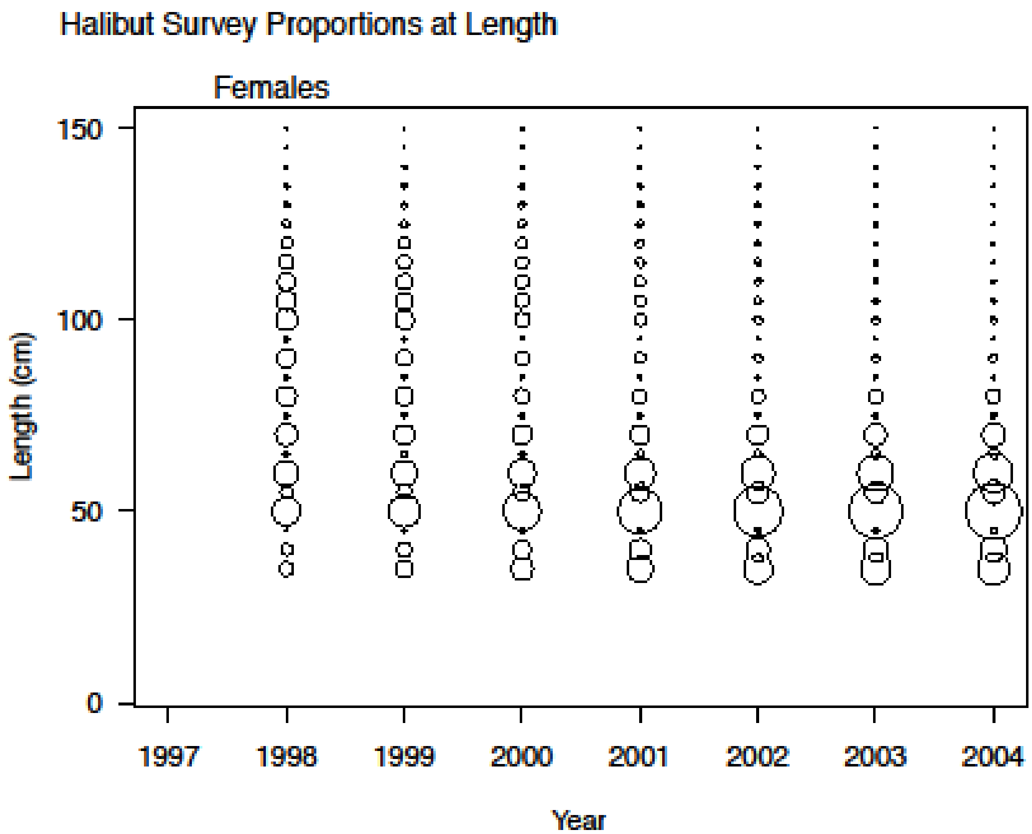


Figure 23. Simulated halibut survey proportions at length used for model testing.

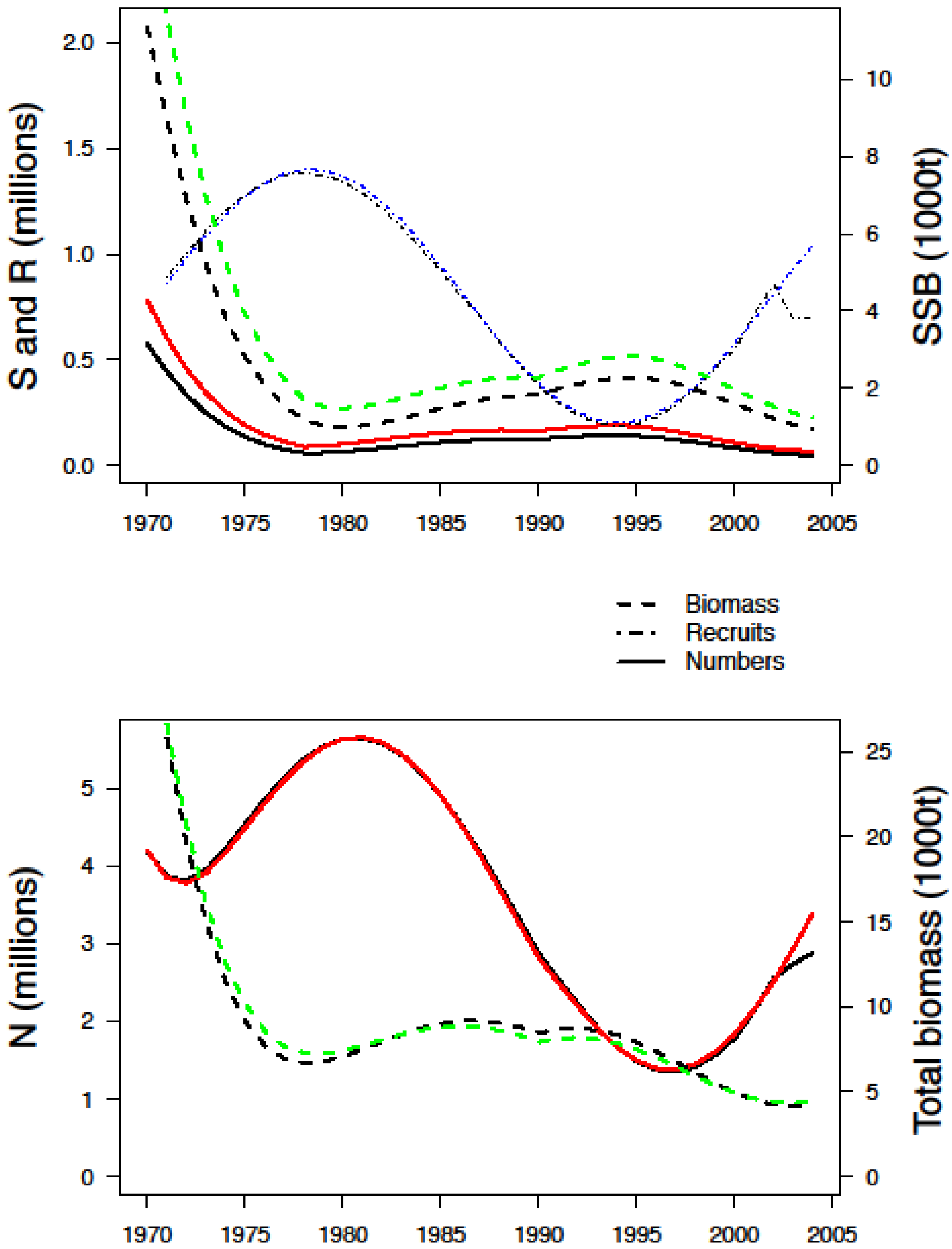


Figure 24. Simulated (in color) and estimated (black) biomass, recruits and numbers.

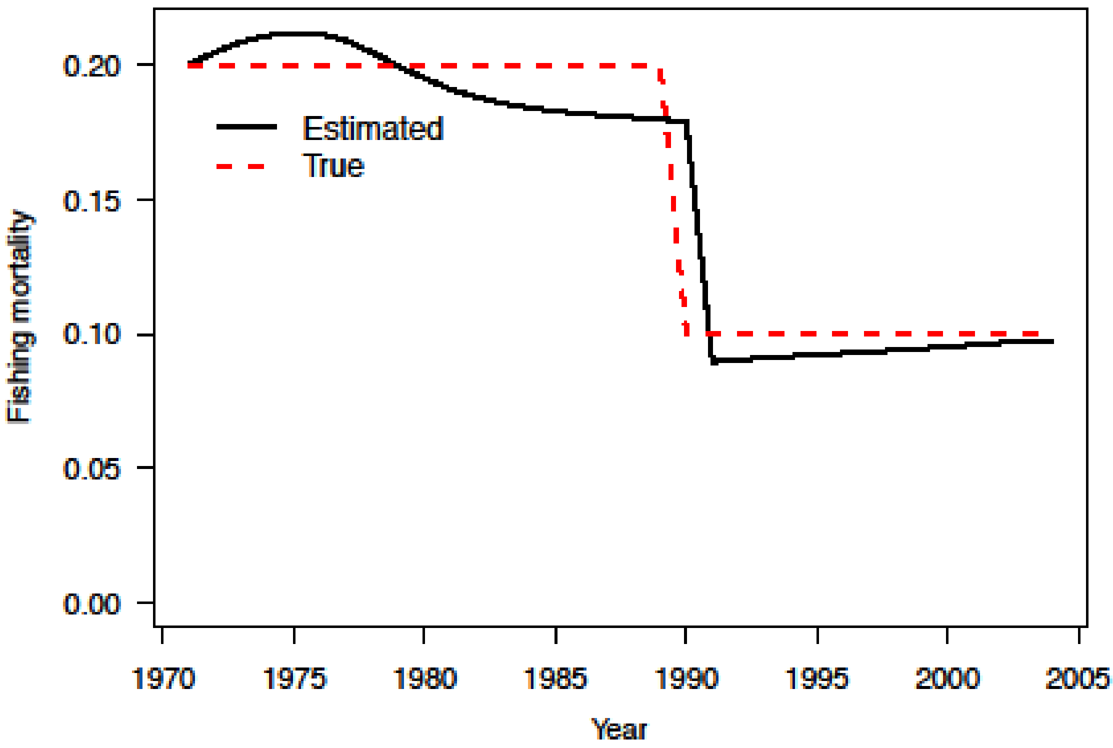


Figure 25. Simulated (dashed line) and estimated (solid line) fishing mortality.

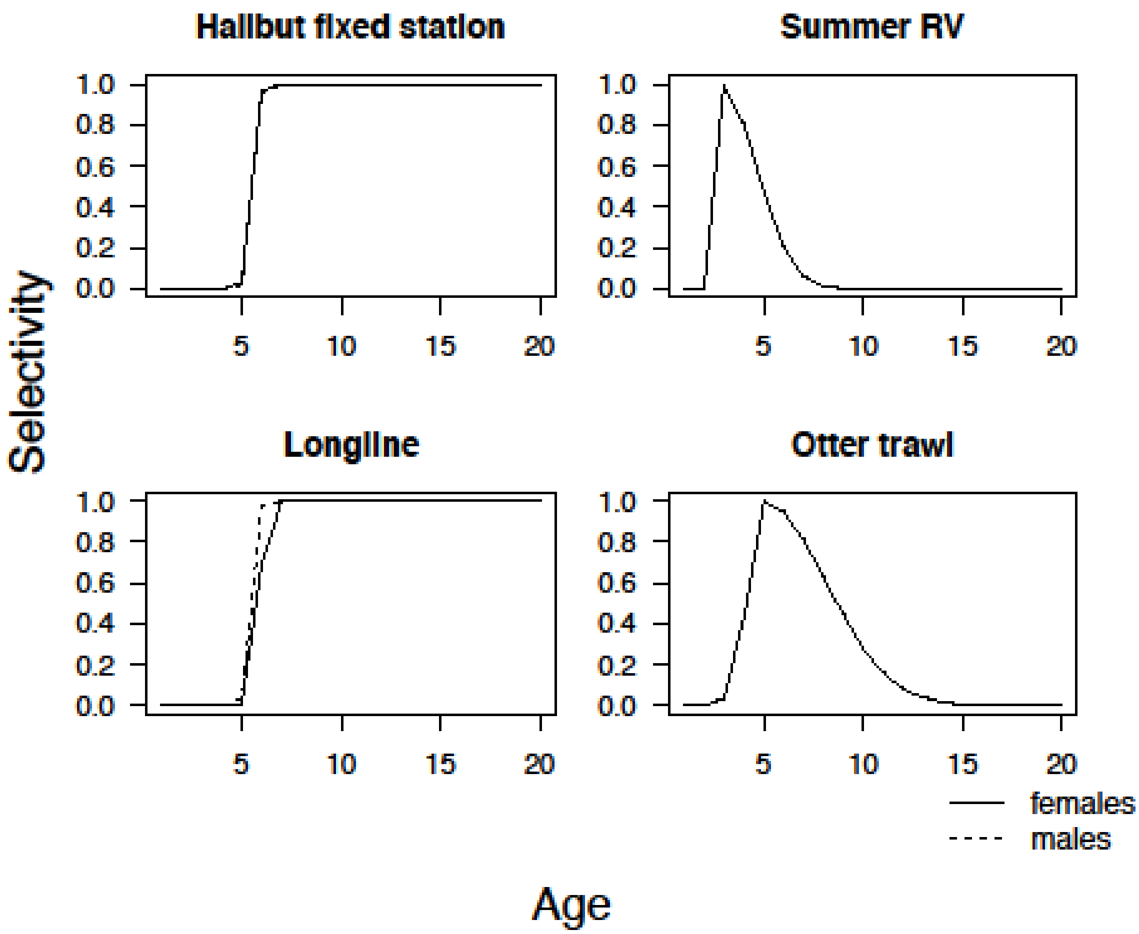


Figure 26. Gear selectivity at age for male and female Atlantic halibut.

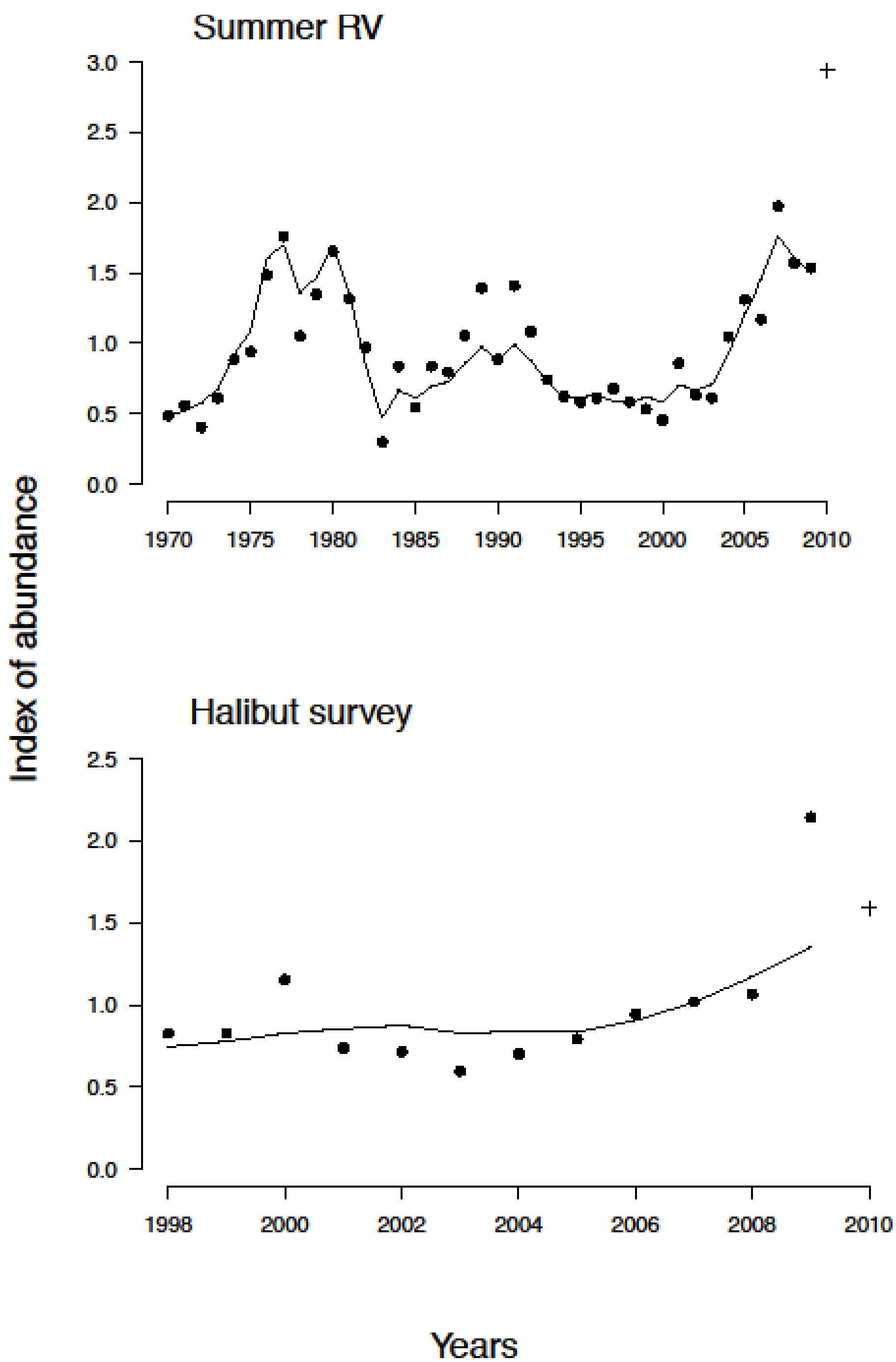


Figure 27. Model fit (line) to abundance indices (points). The model was not fit to the 2010 point (+), but was shown for comparison.

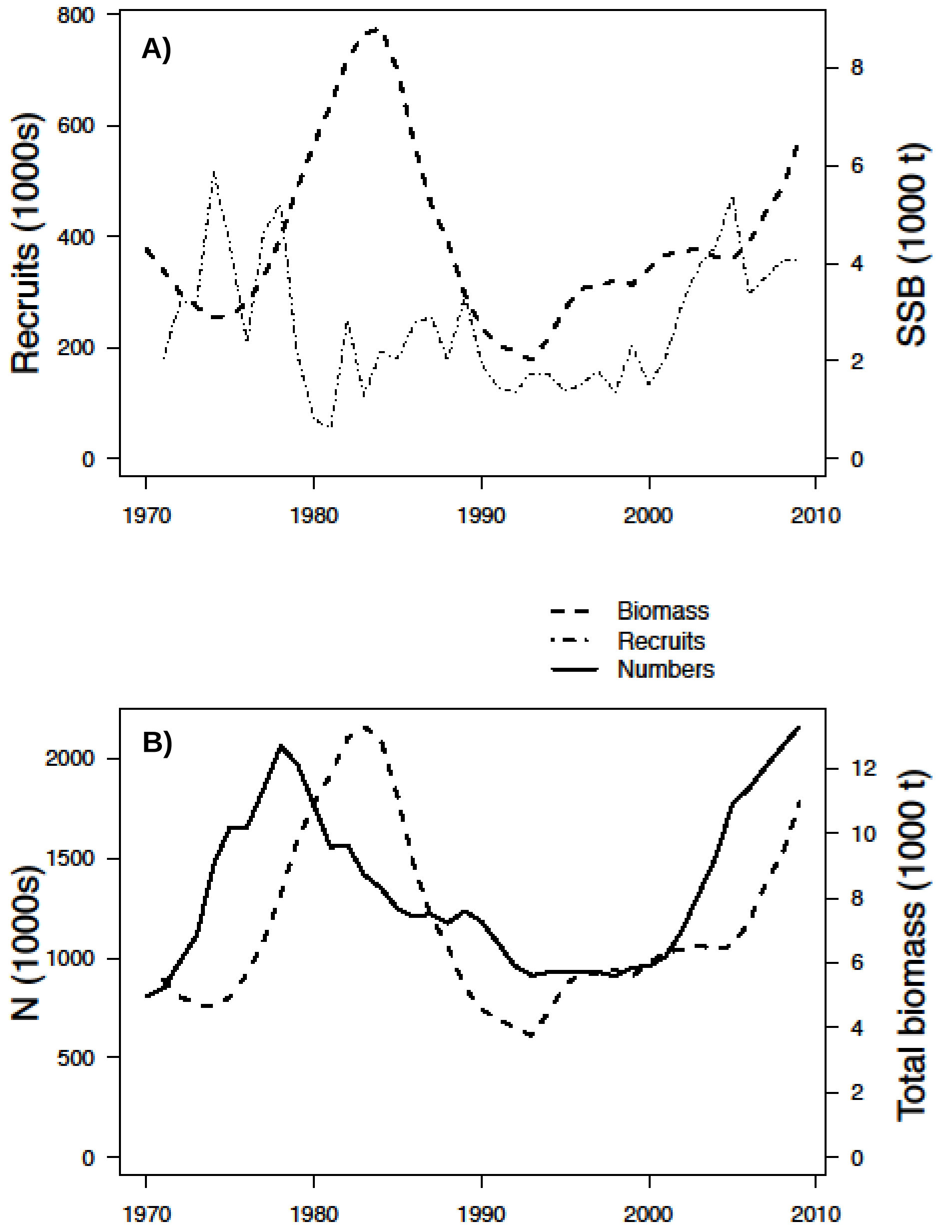


Figure 28. A) Spawning stock biomass, spawner numbers, and the number of age-1 recruits, B) total biomass and total number of Atlantic halibut.

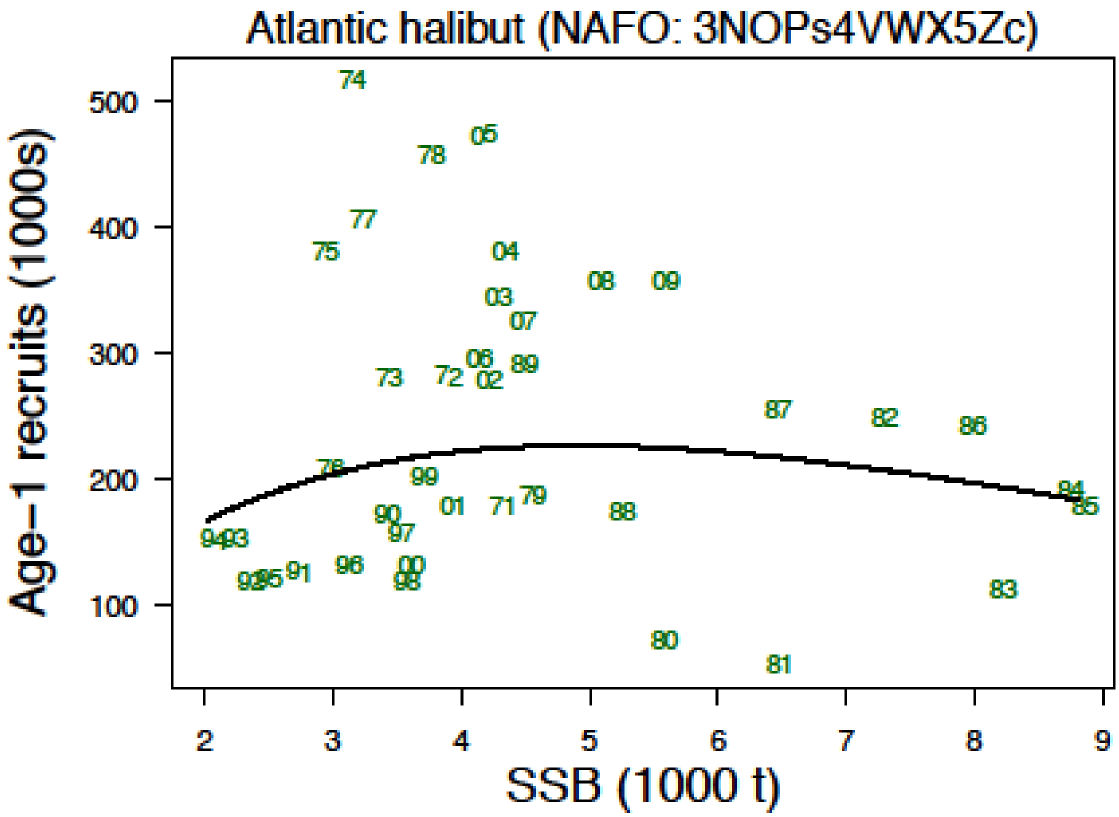


Figure 29. Stock-recruitment relationship for Atlantic halibut. Numbers plotted indicate year at age-1.

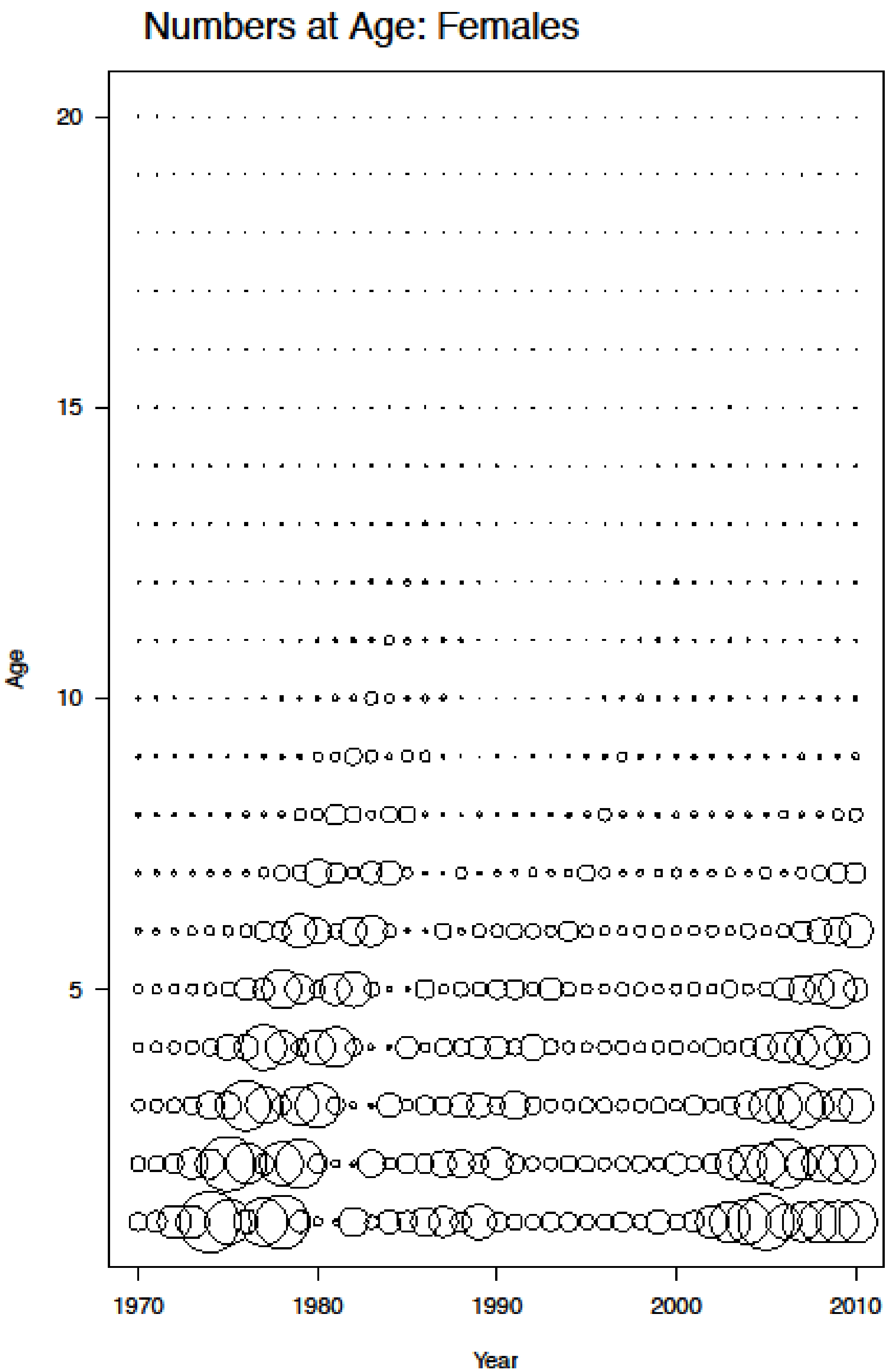


Figure 30. Bubble plot of the predicted number of Atlantic halibut at age. Larger circles indicate large numbers

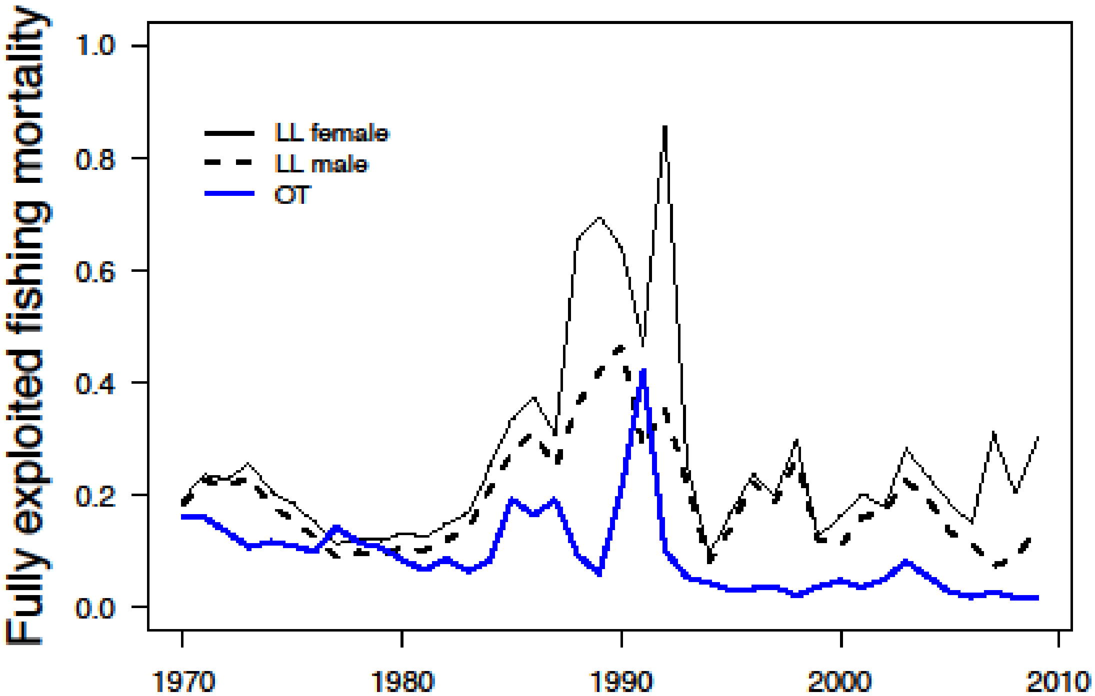


Figure 31. Fishing mortality for fully exploited halibut caught on longline (LL) and otter trawl (OT) gear.

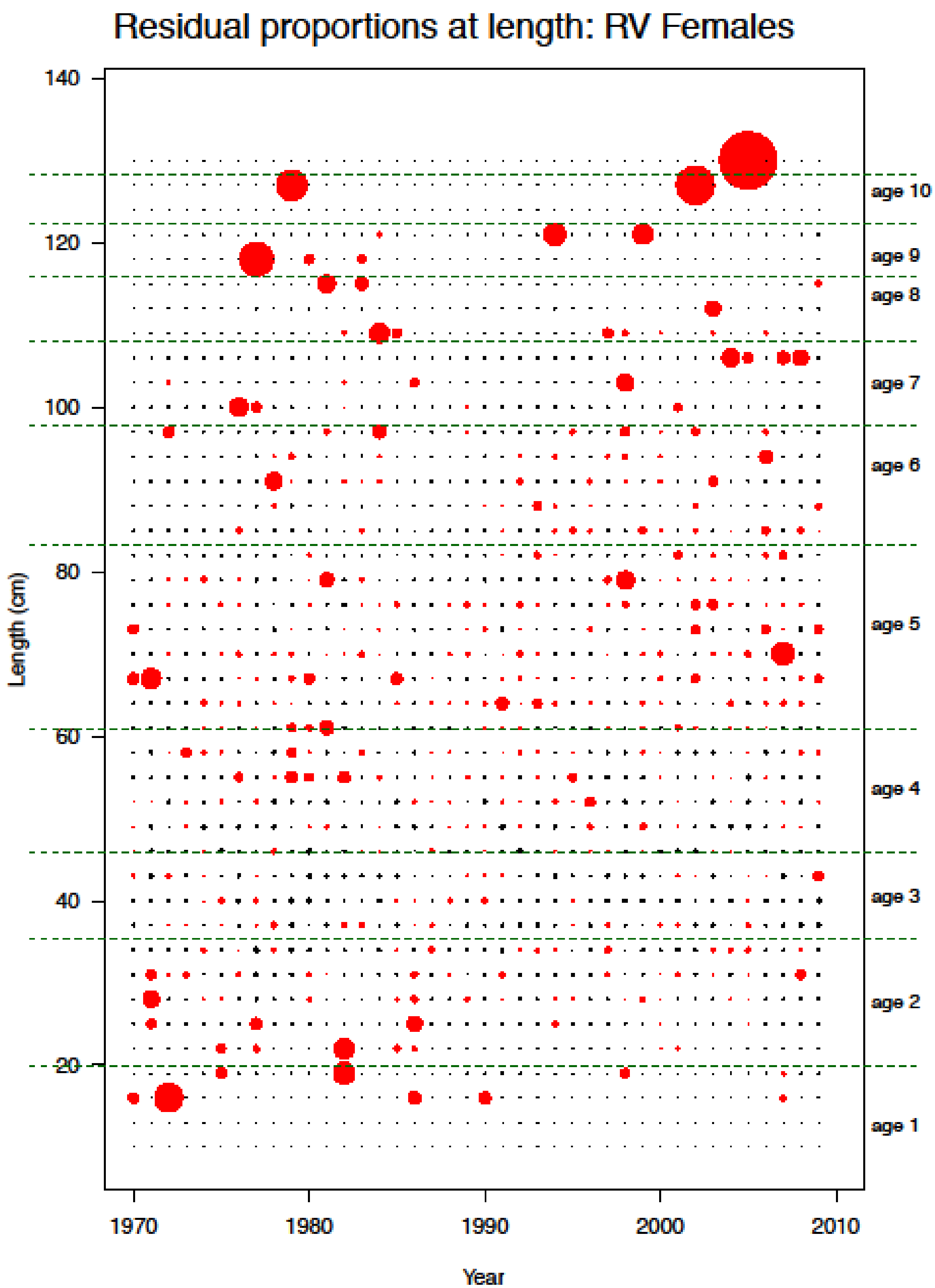


Figure 32. Residual proportions at length of females caught by the RV summer survey. Red: positive residual, black: negative.

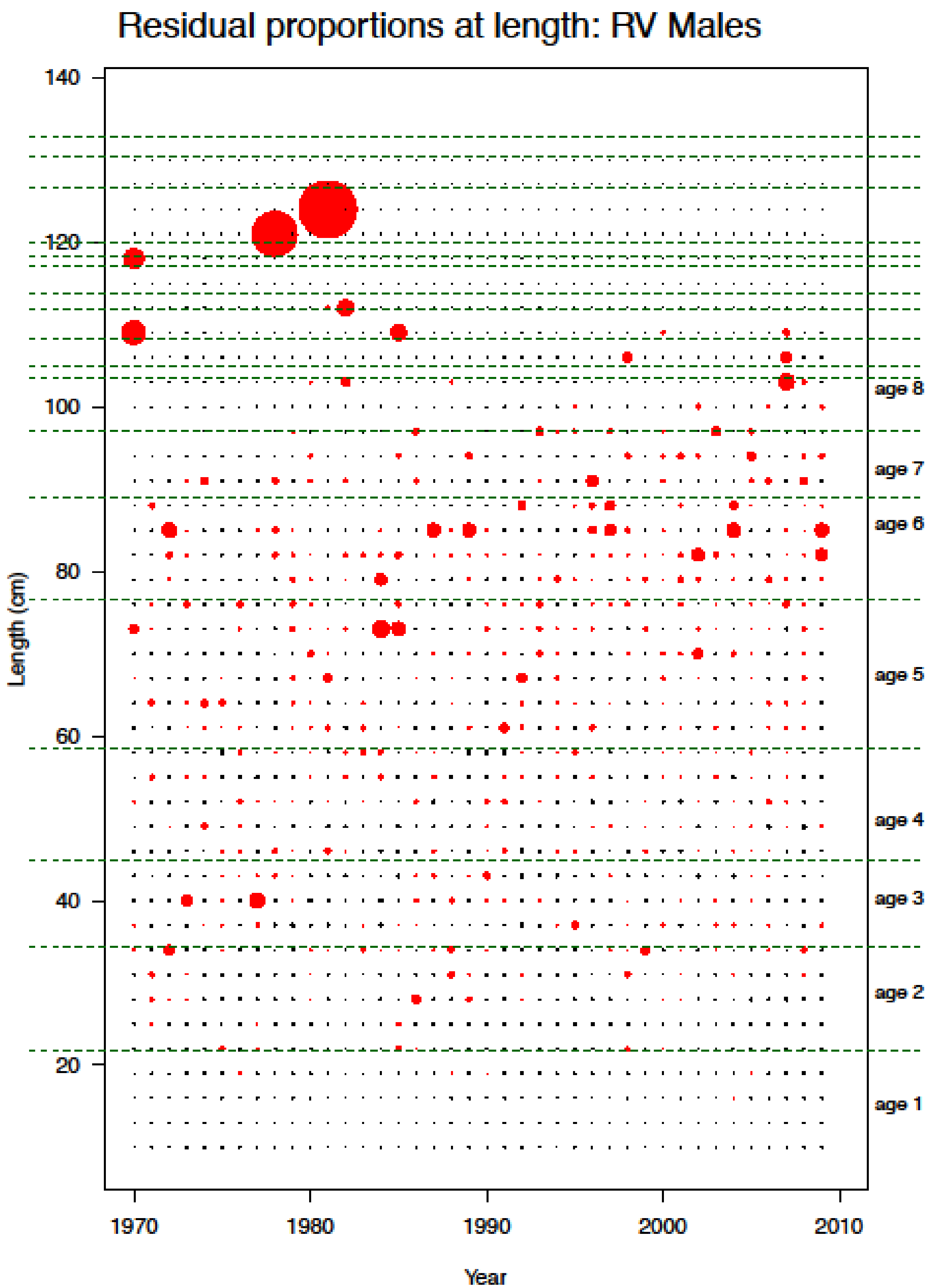


Figure 33. Residual proportions at length of males caught by the RV summer survey. Red: positive residual, black: negative.

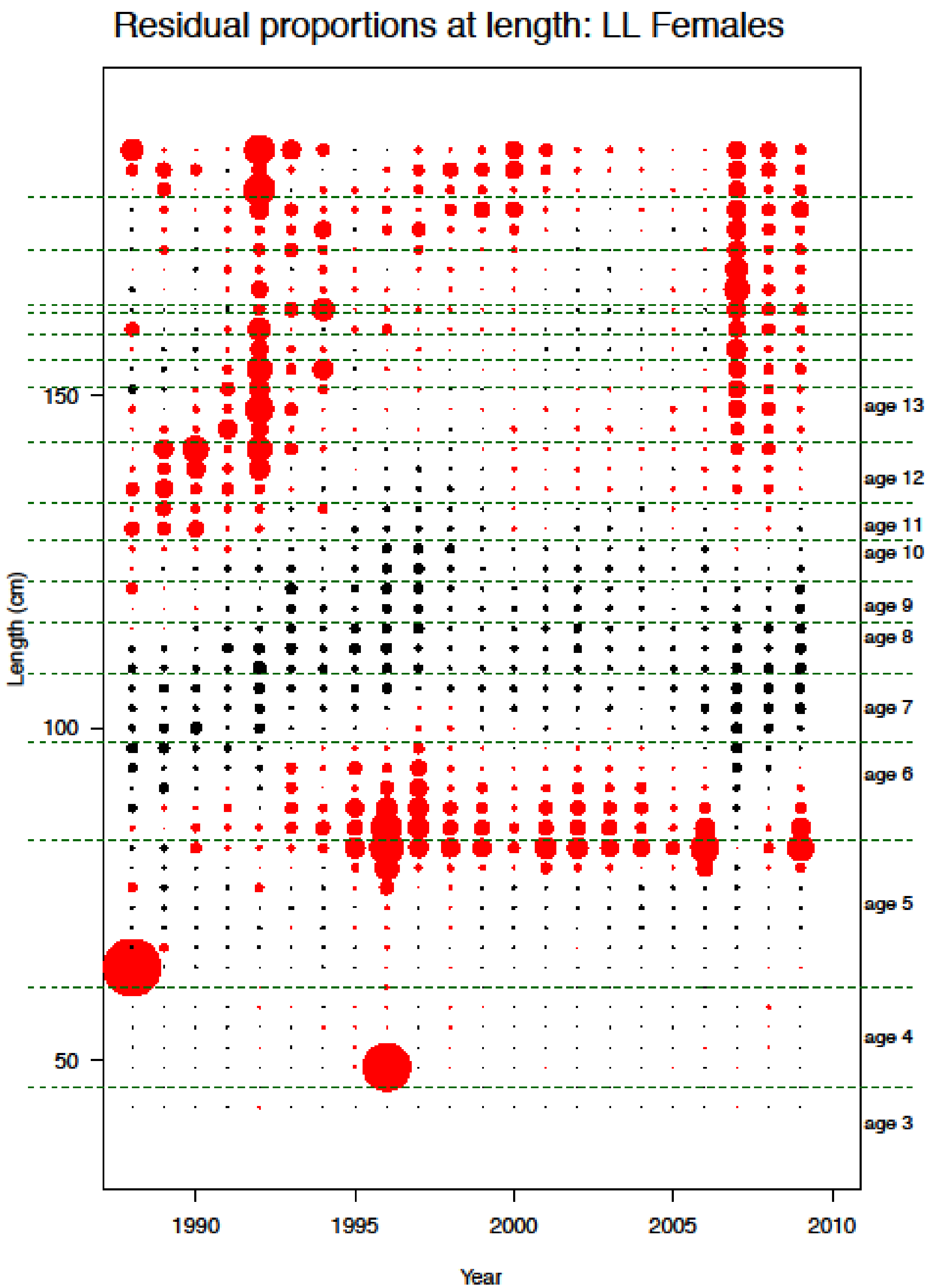


Figure 34. Residual proportions at length of females caught by the longline fishery. Red: positive residual, black: negative.

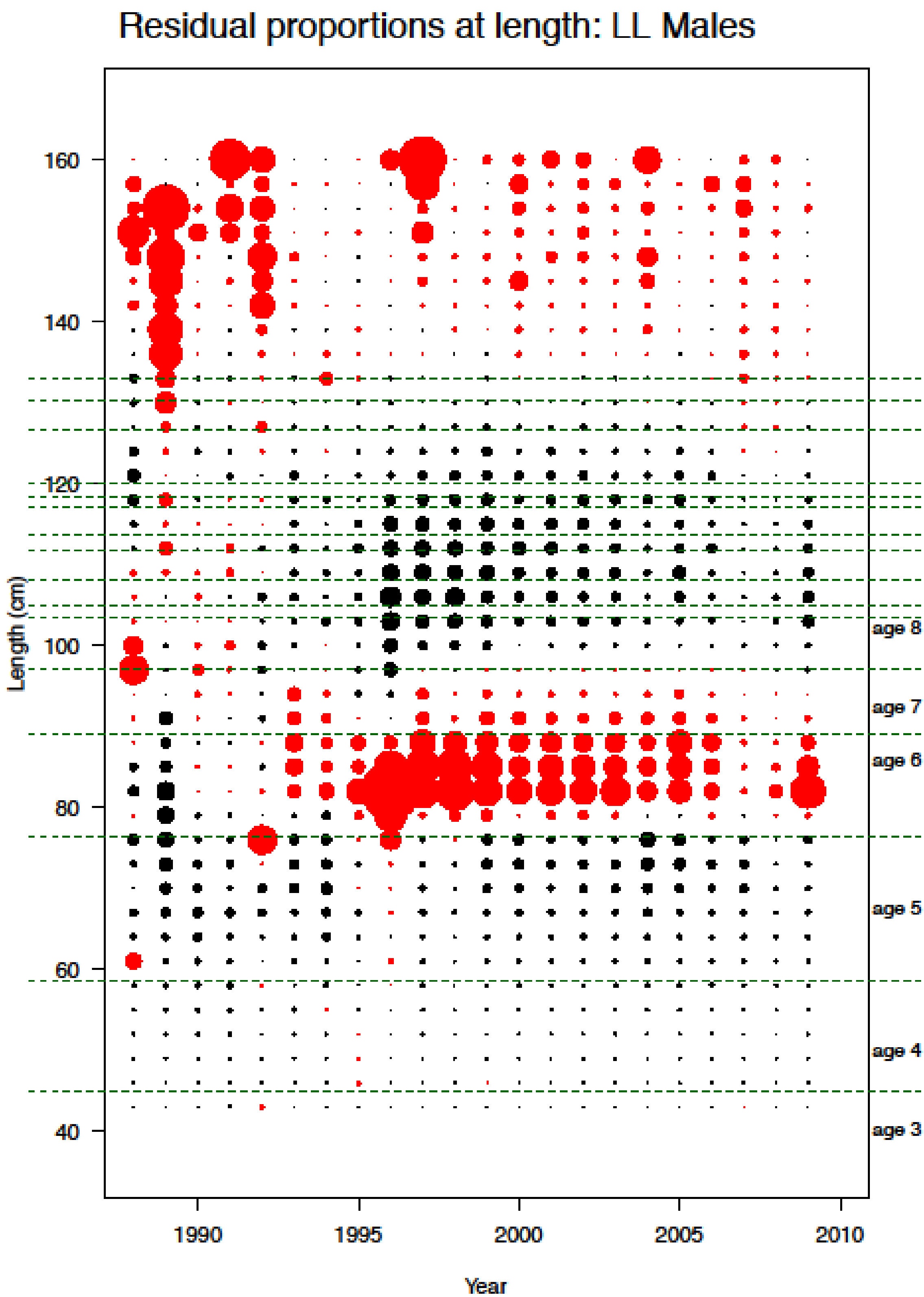


Figure 35. Residual proportions at length of males caught by the longline fishery. Red: positive residual, black: negative.

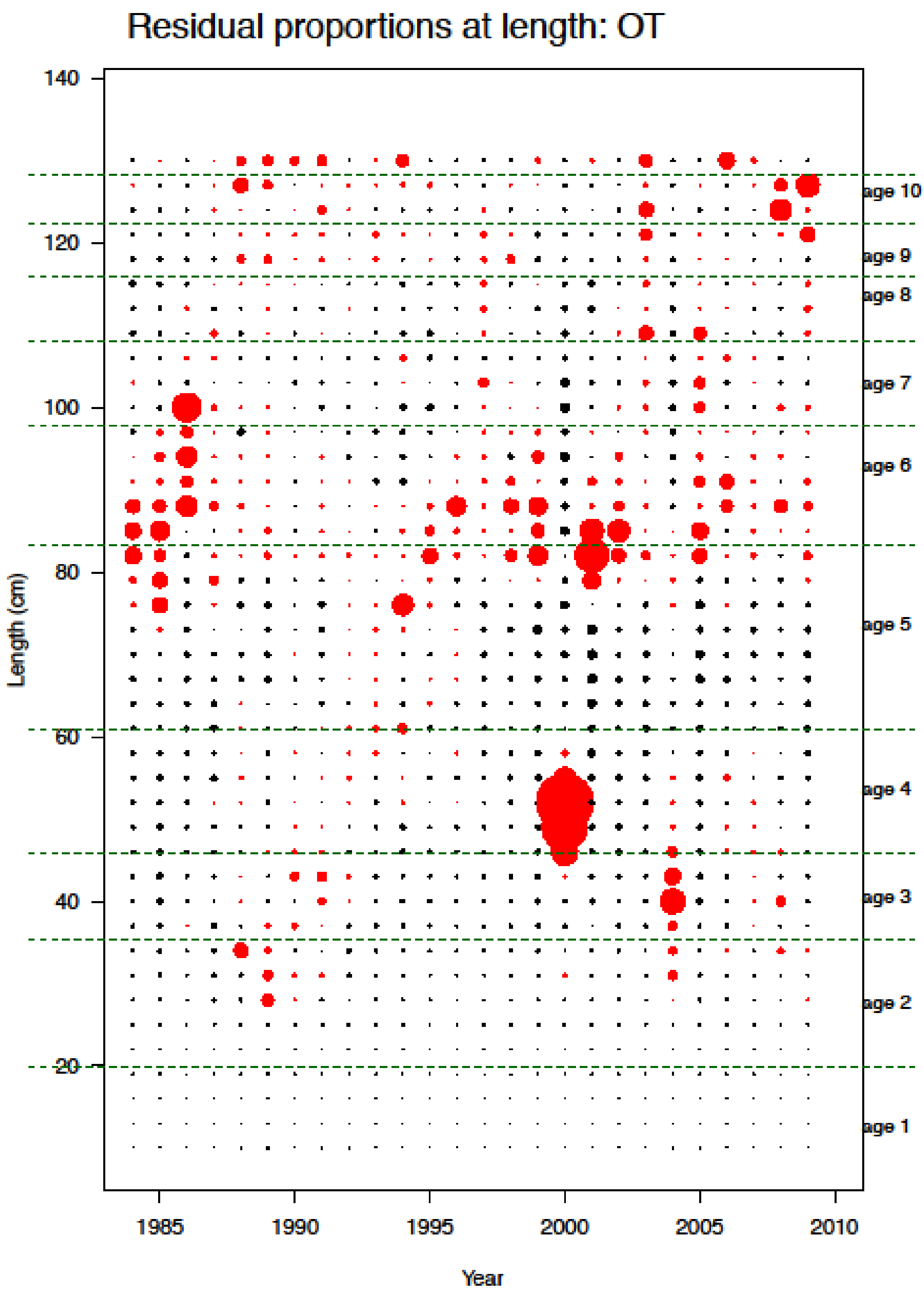


Figure 36. Residual proportions at length caught by the otter trawl fishery. Red: positive residual, black: negative.

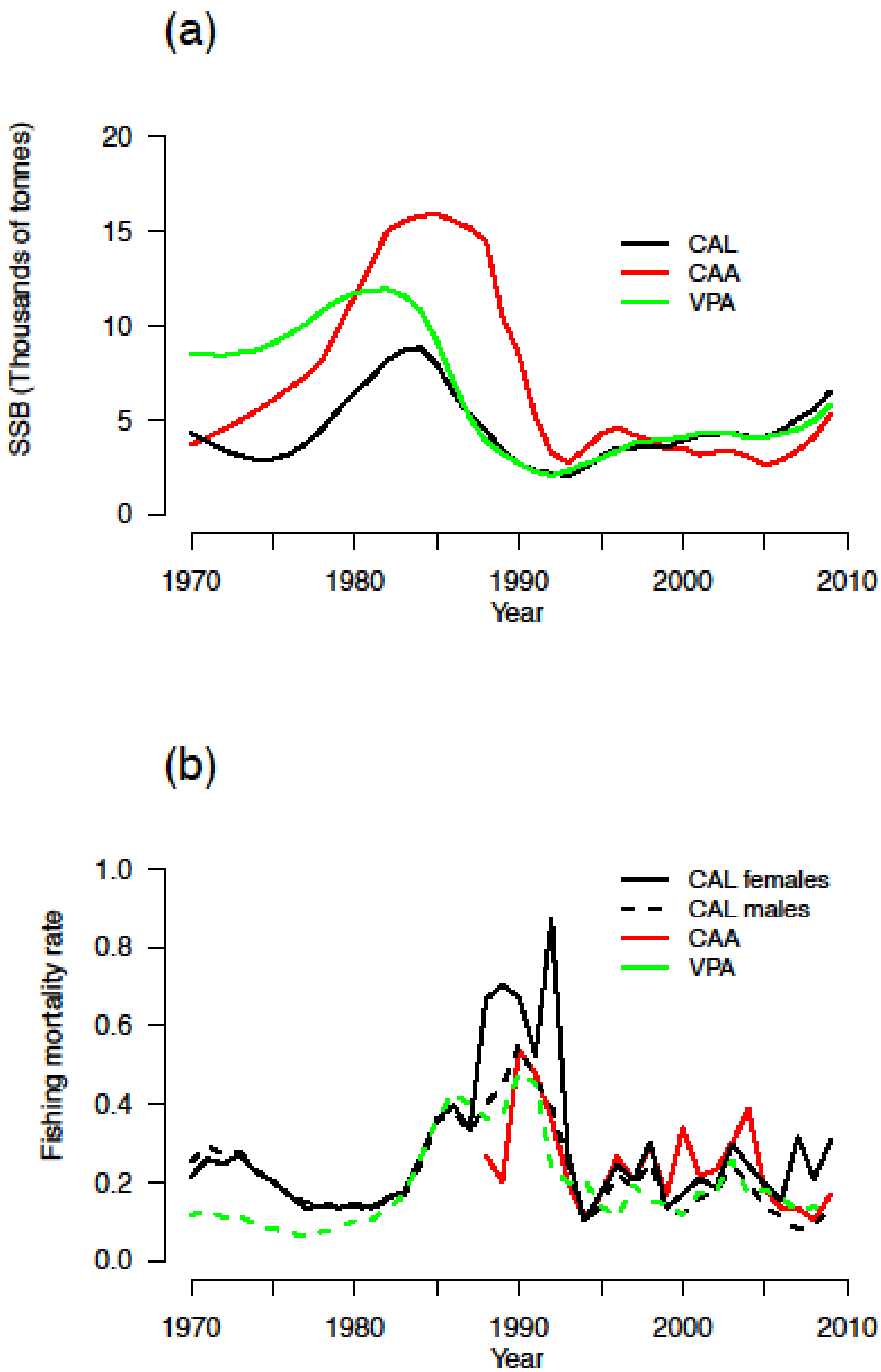


Figure 37. Comparisons between the catch at length model (CAL; used in this assessment), the statistical catch-at-age (CAA) model and virtual population analysis (VPA for a) spawning stock biomass and b) fishing mortality.

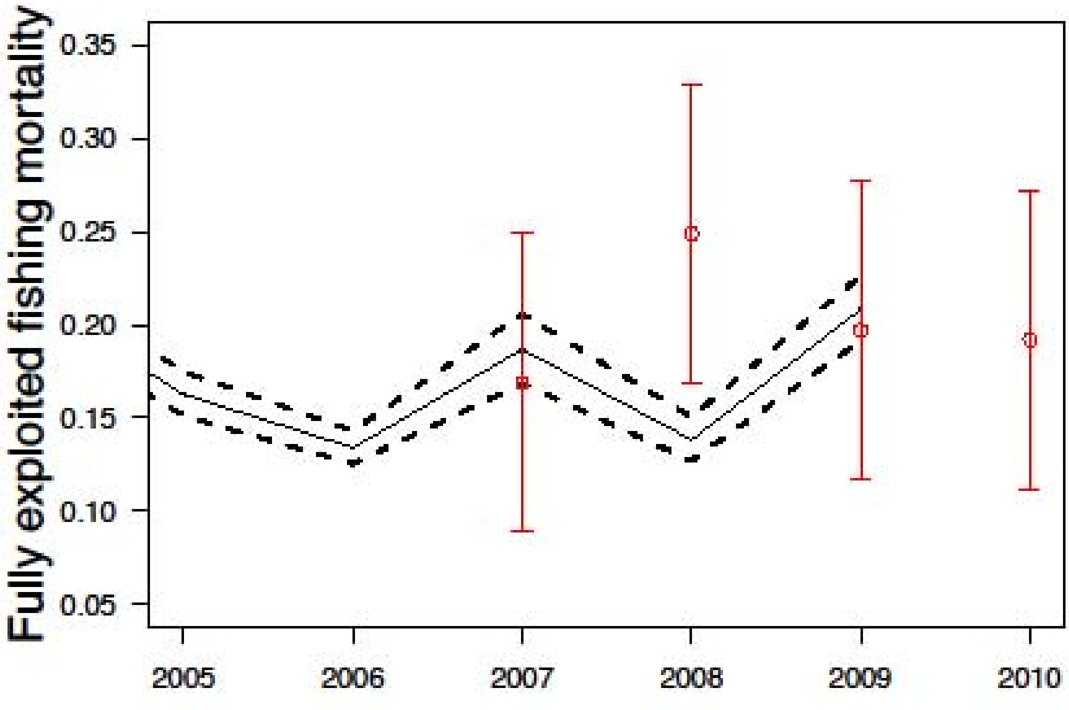


Figure 38. Fully exploited fishing mortality calculated as a weighted average of male and female fishing mortality for ages 8 to 20 (solid line) ± 2SE (dashed lines). Fishing mortality for halibut >81cm estimated from tagging (points ± 2SE, Den Heyer et al. 2011).

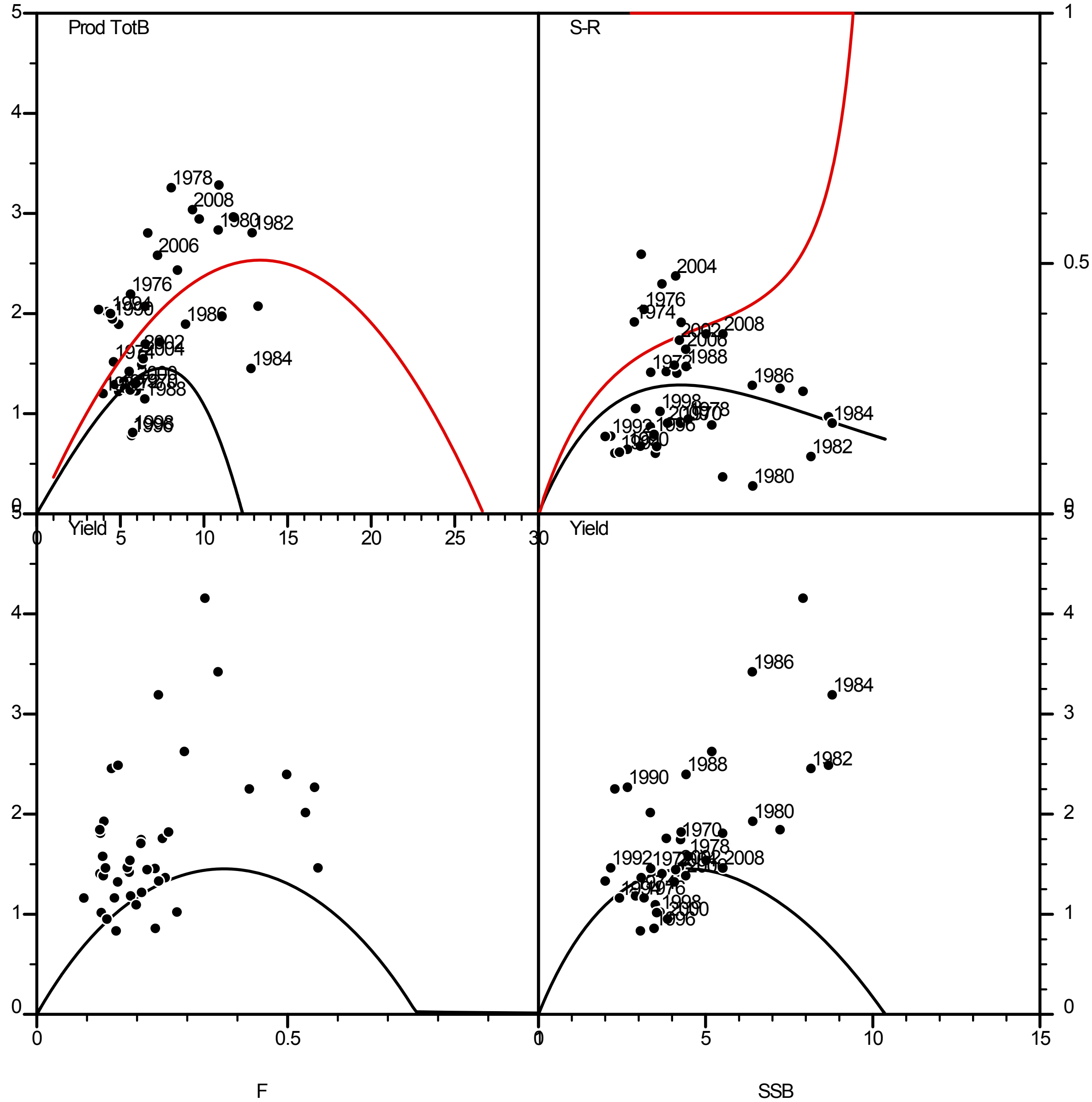


Figure 39. Sissenwine-Shepherd production model. The upper left plot is production as a function of total biomass (in 1000t) with equilibrium lines shown. The black line is based on stock-recruit data while the red line is from the production data. The peak of this line at 1450t is MSY. The upper right plot is a stock-recruit relationship showing a Ricker curve. The lower left plot is yield (in 1000t) as a function of fully recruited fishing mortality, and it shows Fmsy at 0.36. And the lower right plot is yield as a function of spawning stock biomass.

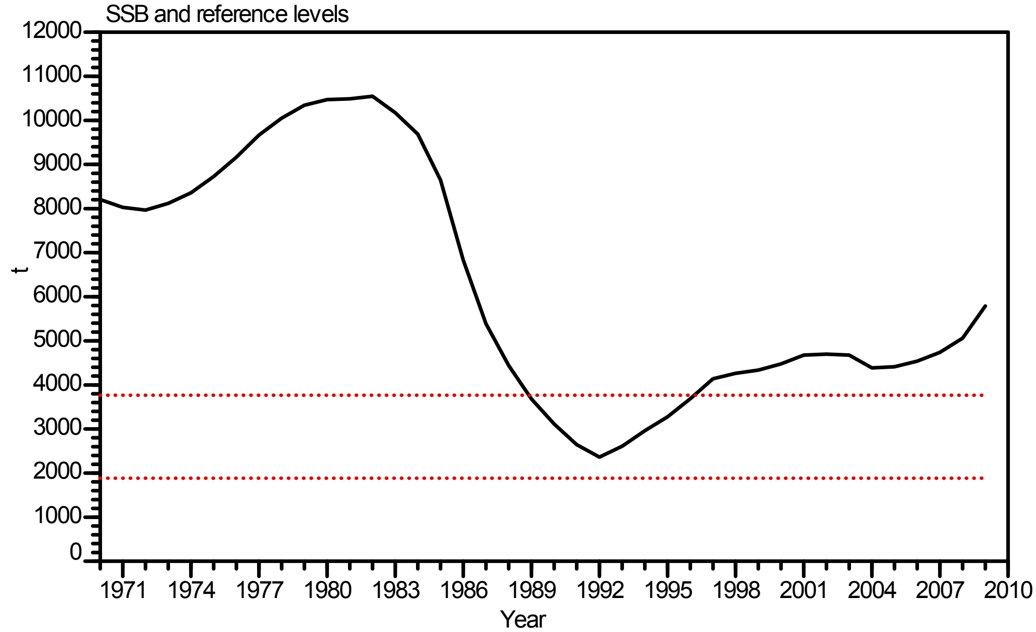


Figure 40. Spawning stock biomass plotted with trial biological reference levels (80 and 40% BMSY).

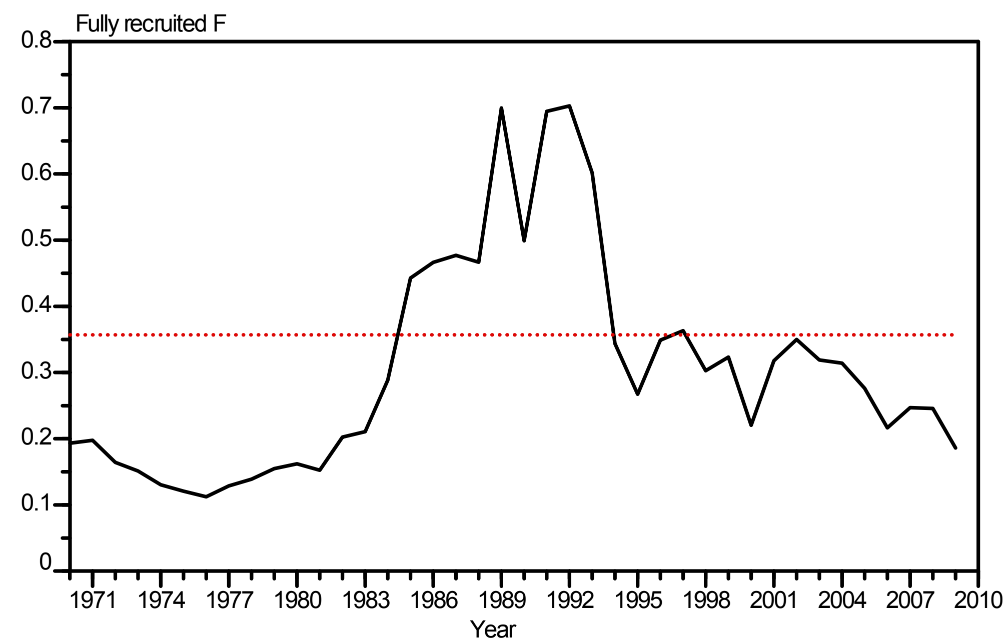


Figure 41. Fully recruited fishing mortality plotted with trial reference level (F=0.36).

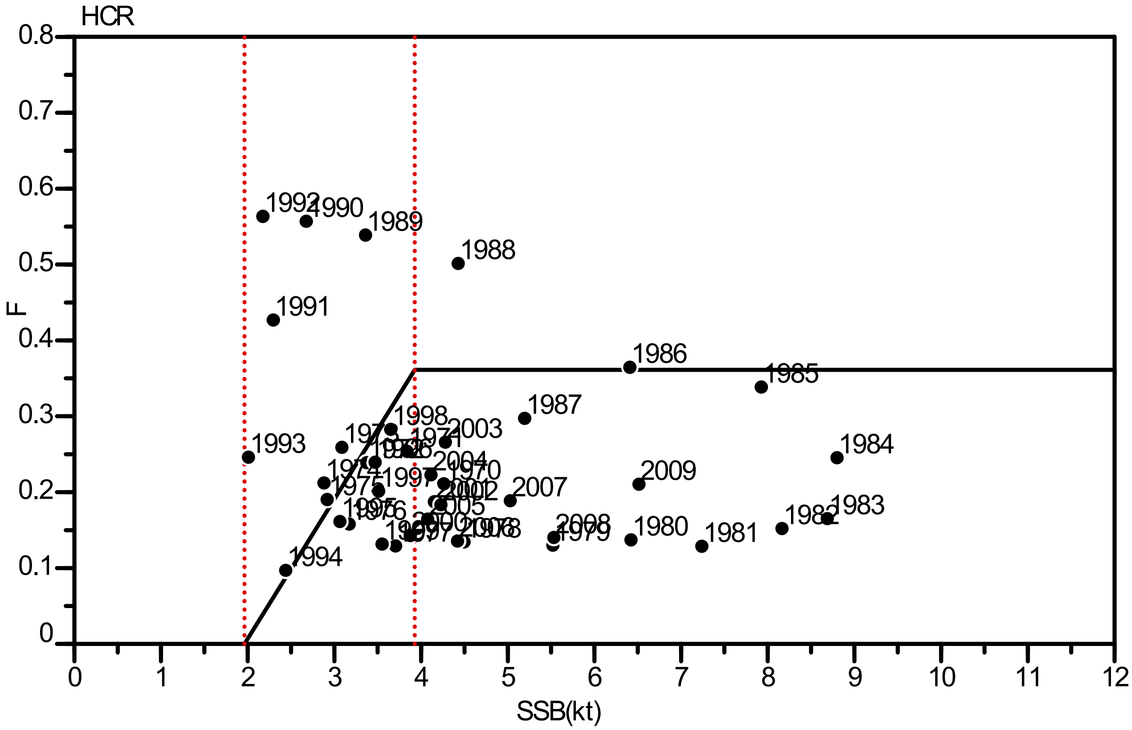
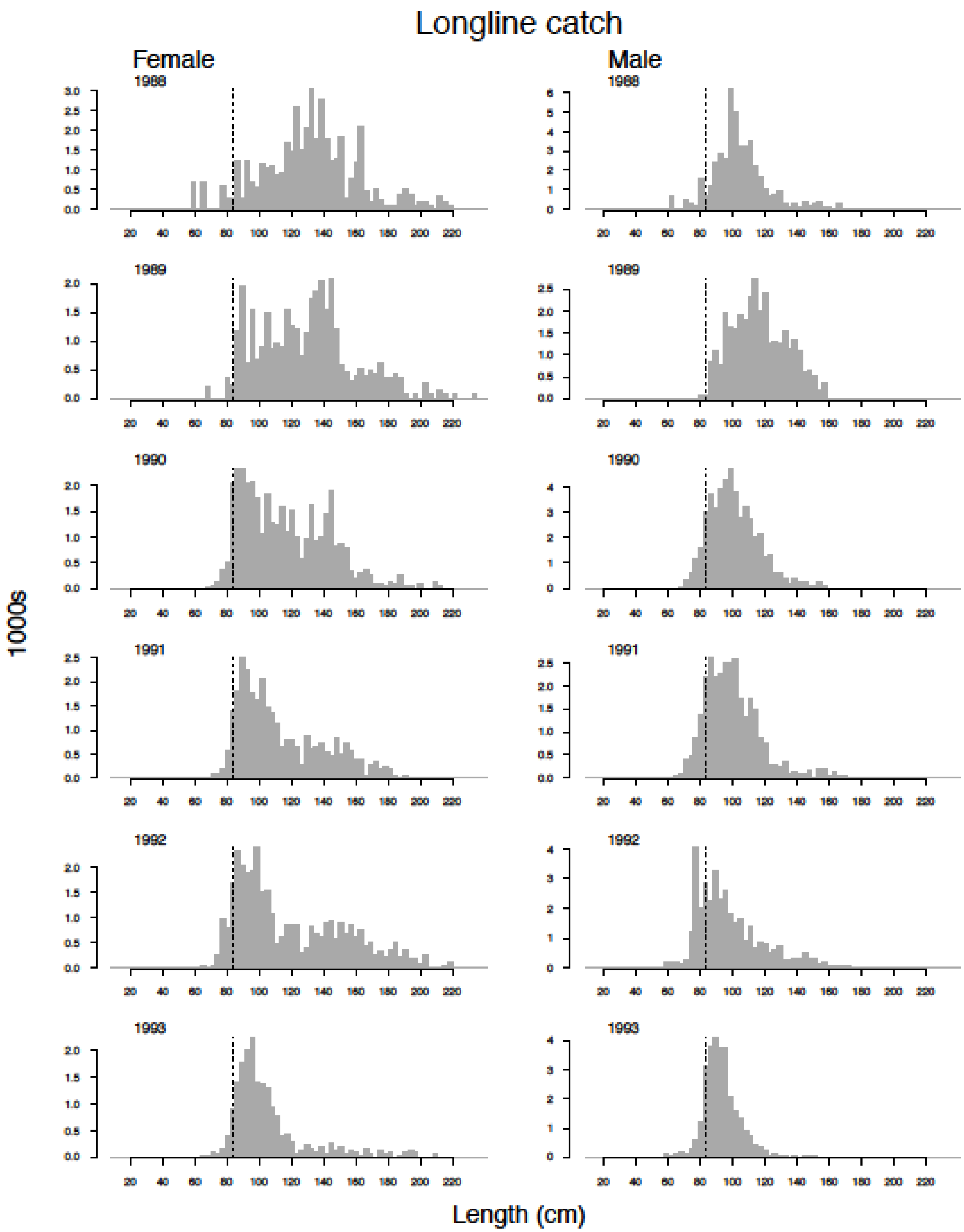
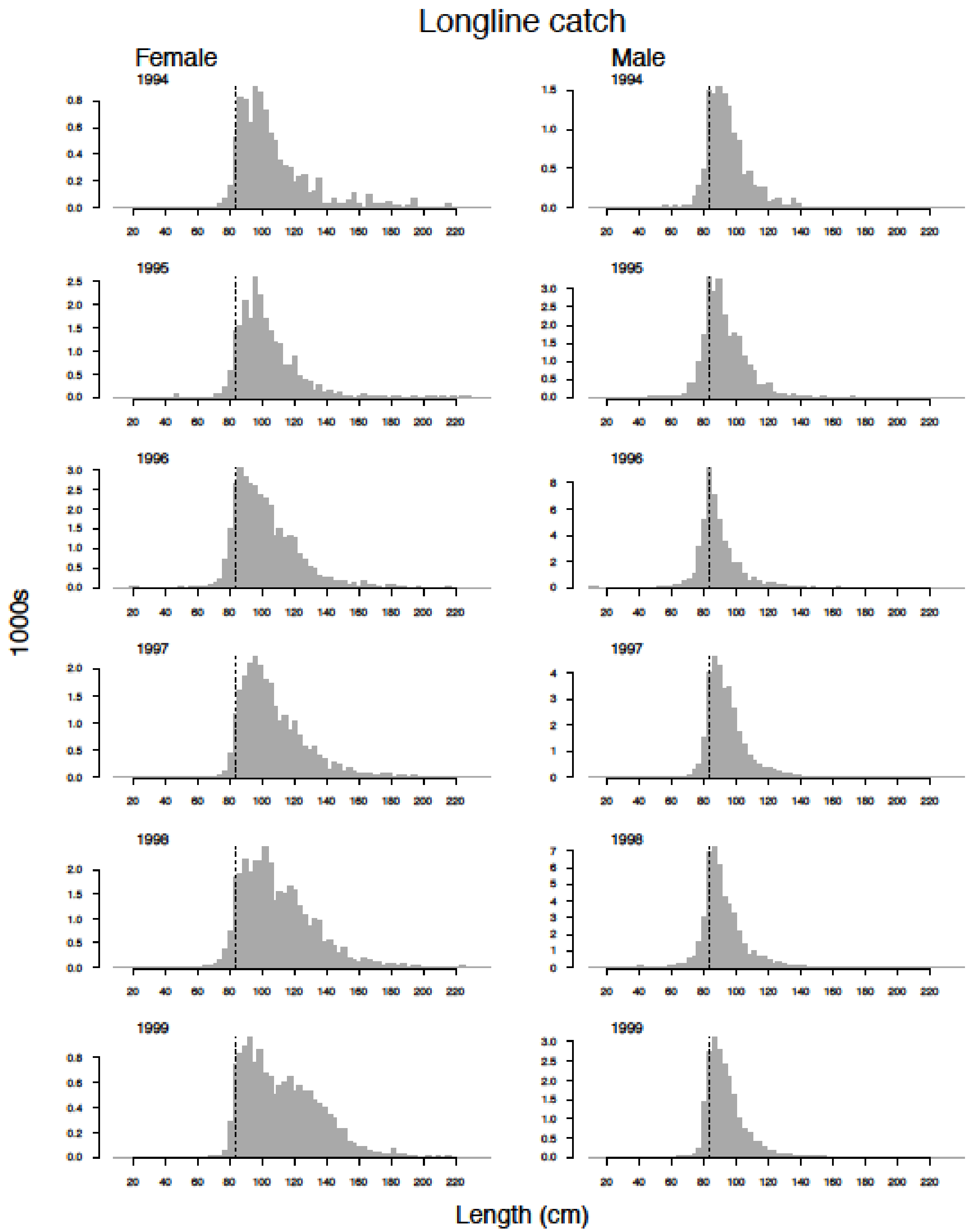
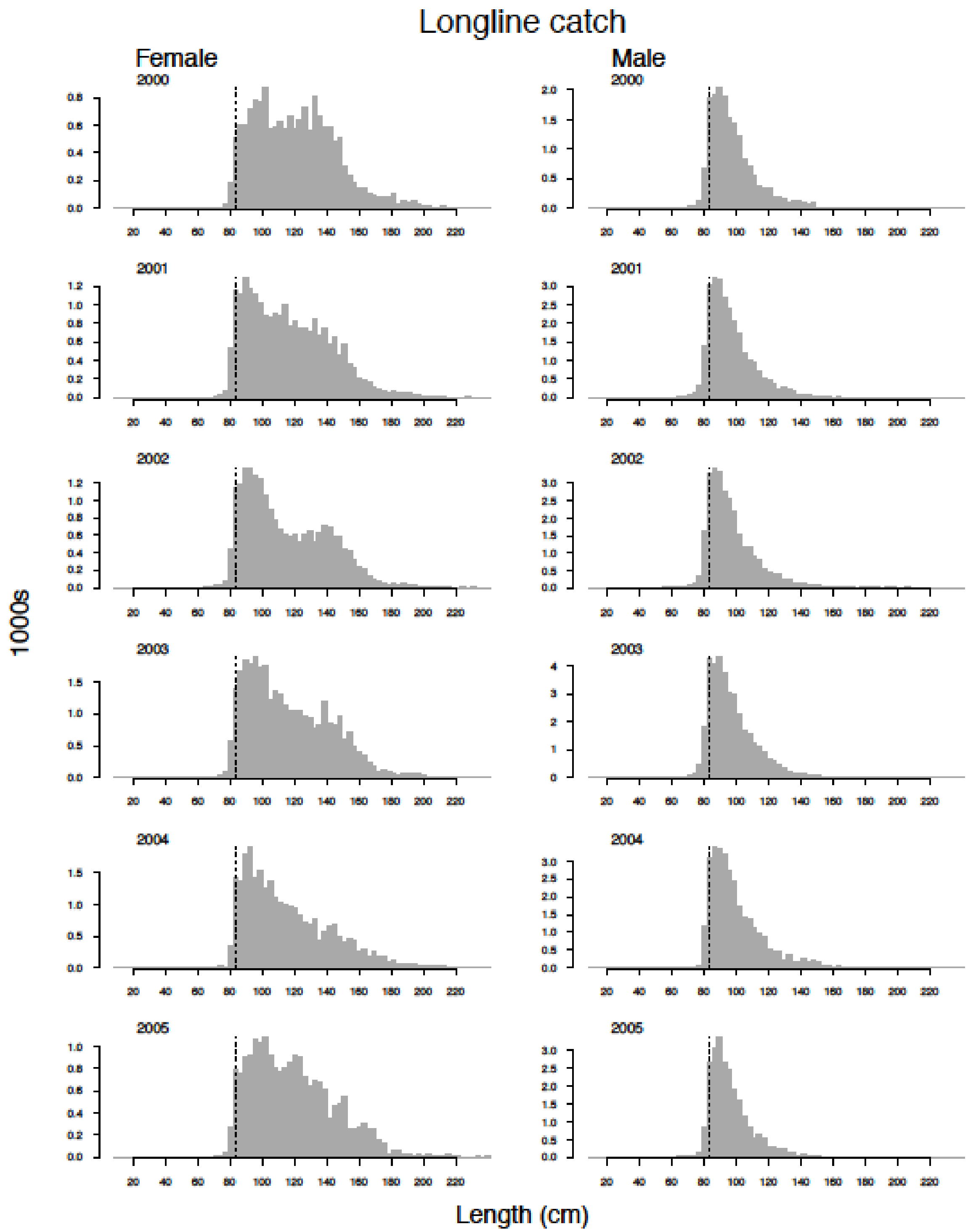


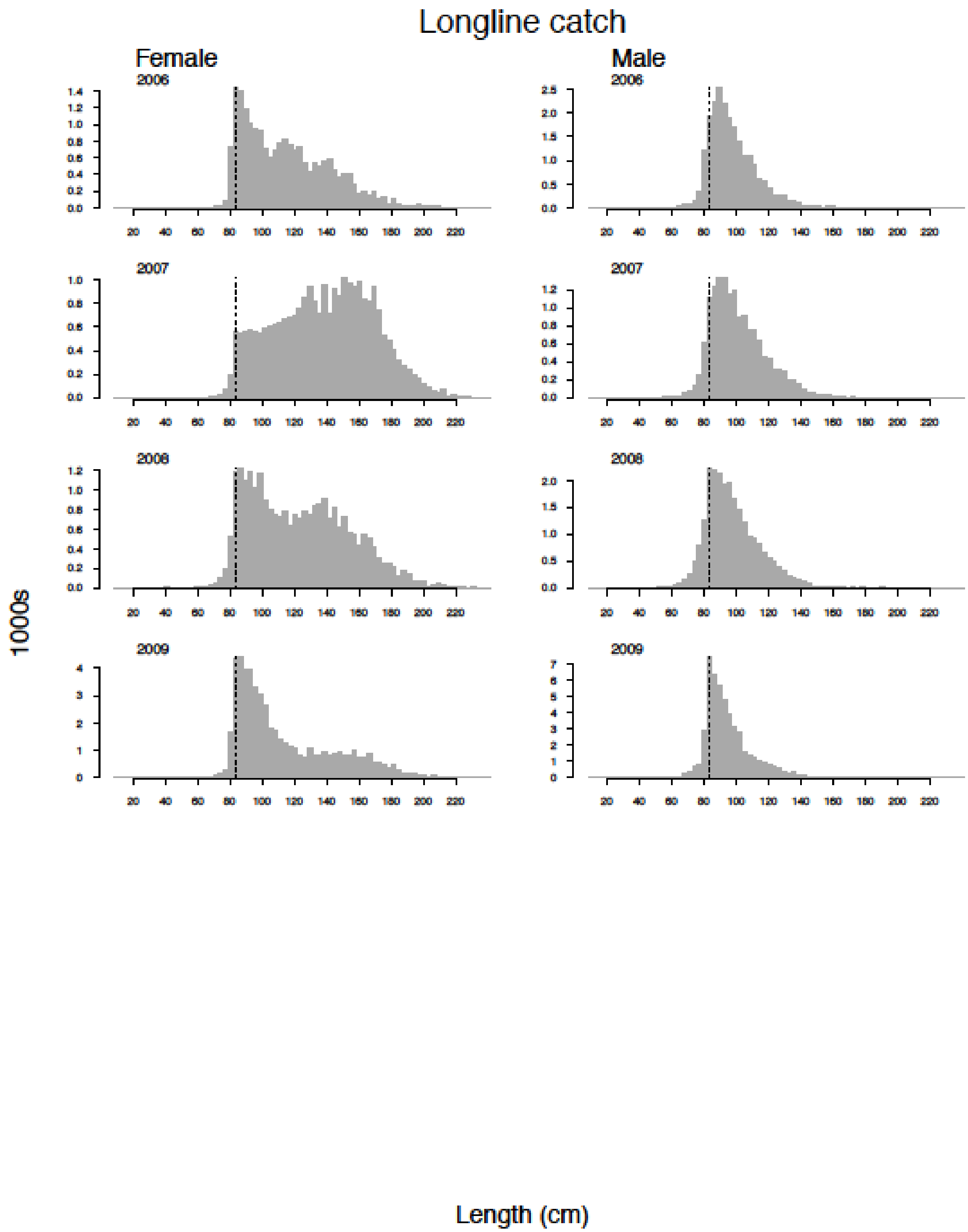
Figure 42. Harvest control rule for halibut using CAL model results. The red vertical lines mark the boundaries between critical, cautious and healthy domains. The history of the stock is shown as labelled points.

Appendix A. *Atlantic halibut length frequency and proportions at length.*

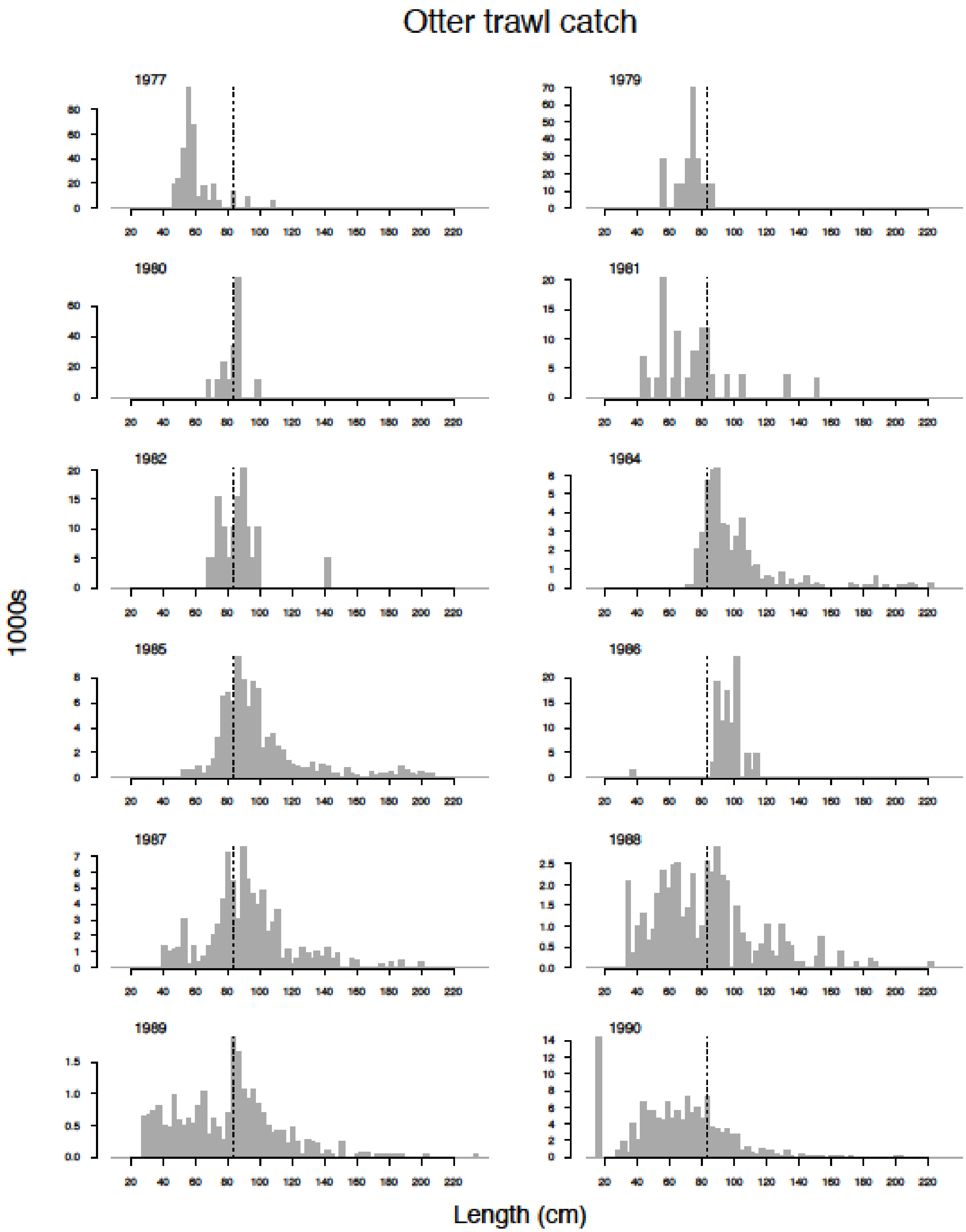


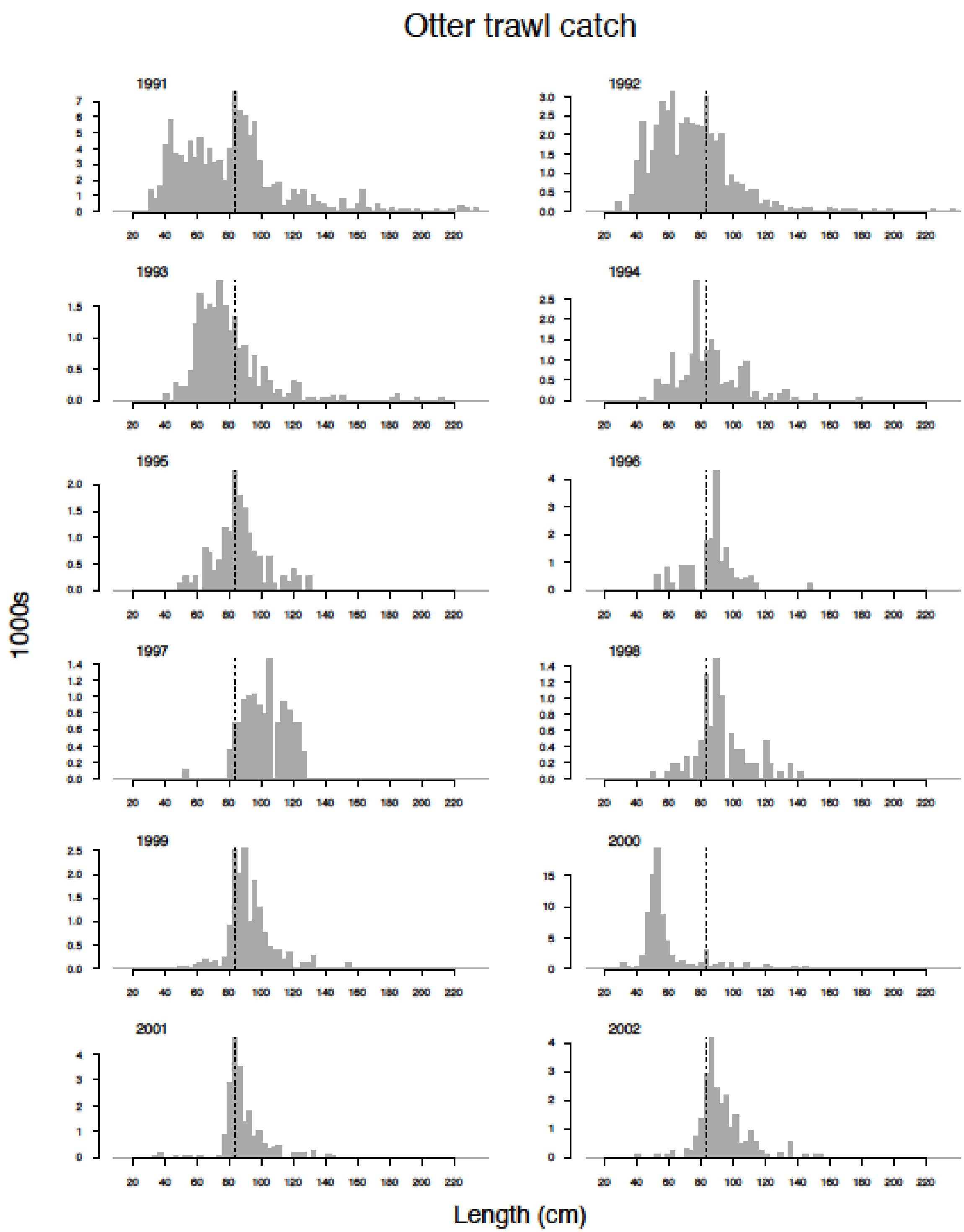

Longline catch
Female
Male
1994
1995
1996
1997
1998
1999
1000s
Length (cm)

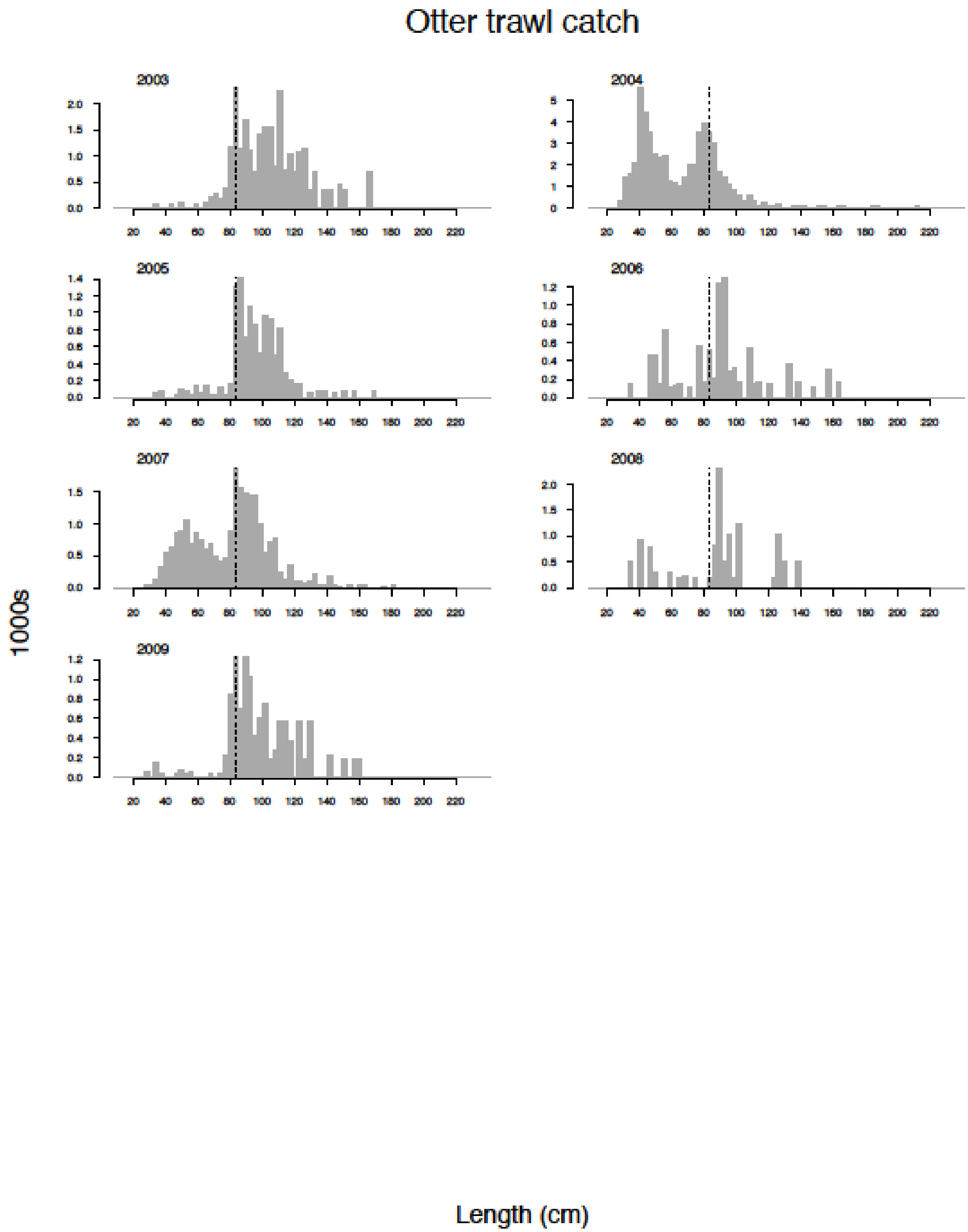

Longline catch
Female
Male
2000
2001
2002
2003
2004
2005
1000s
Length (cm)

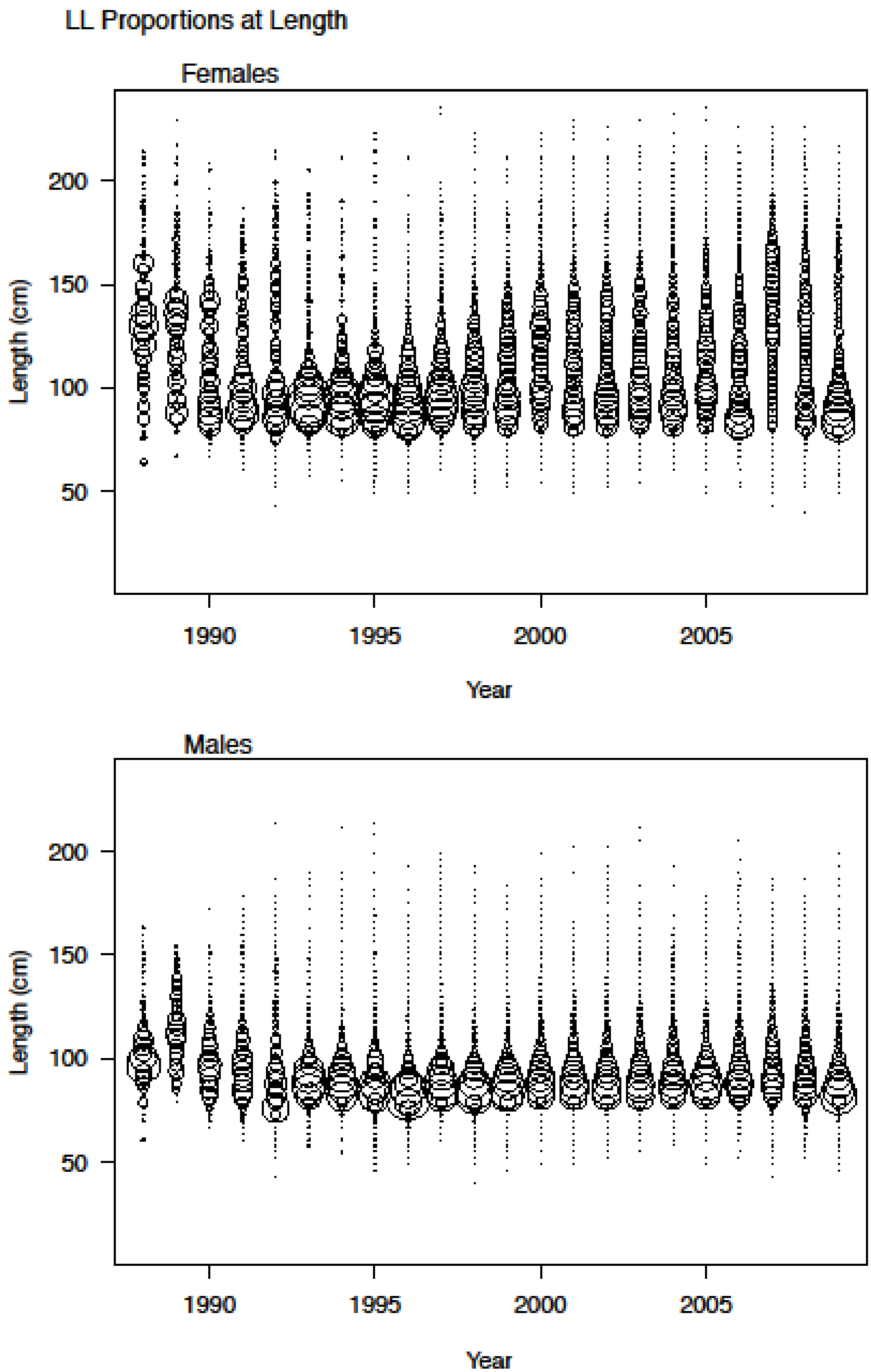


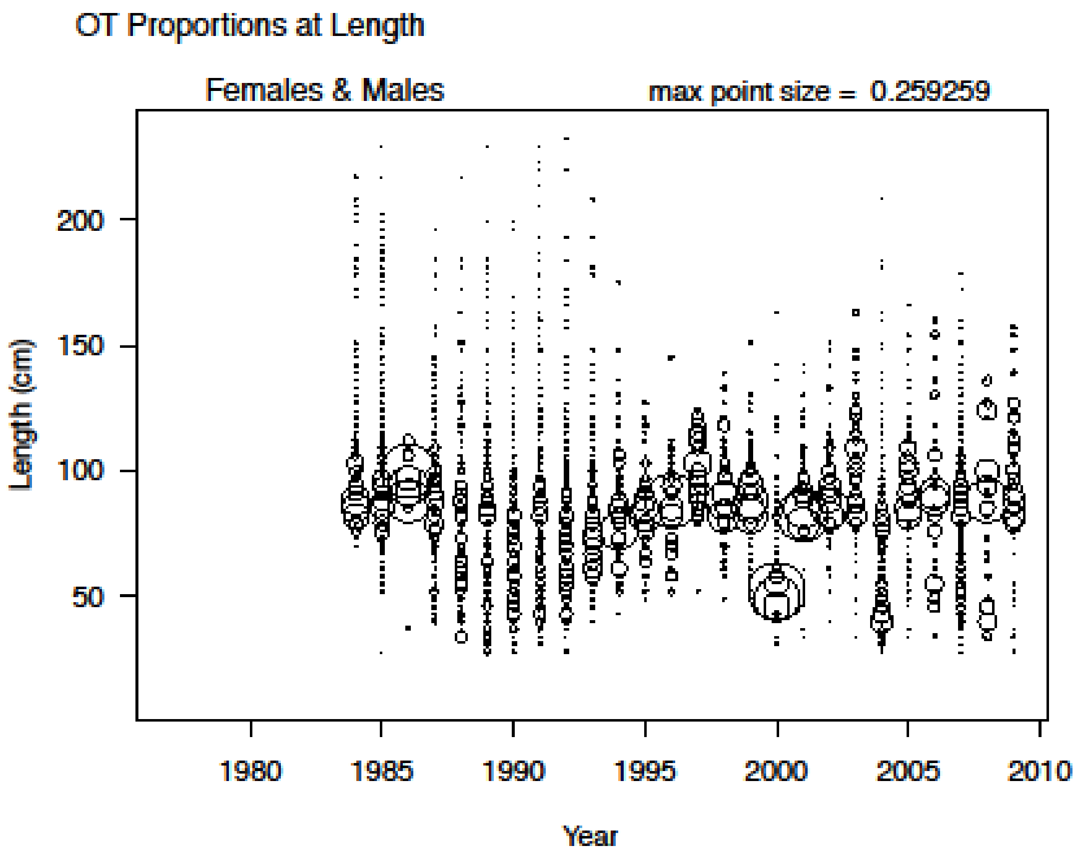
Longline catch
Female
Male
2006
2007
2008
2009
1000s
Length (cm)

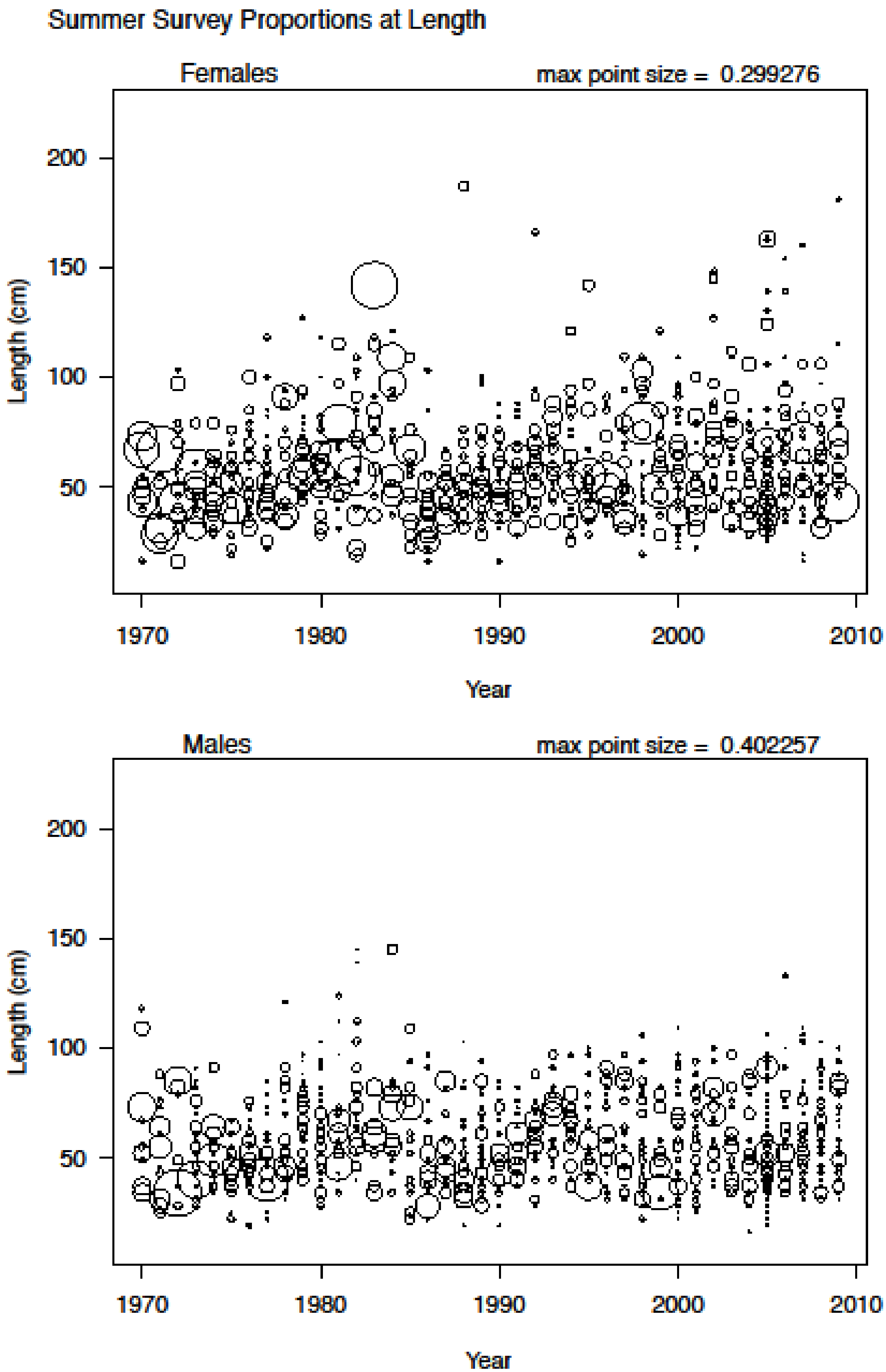

Otter trawl catch
1977
1979
1980
1981
1982
1984
1985
1986
1987
1988
1989
1990
1000s
Length (cm)

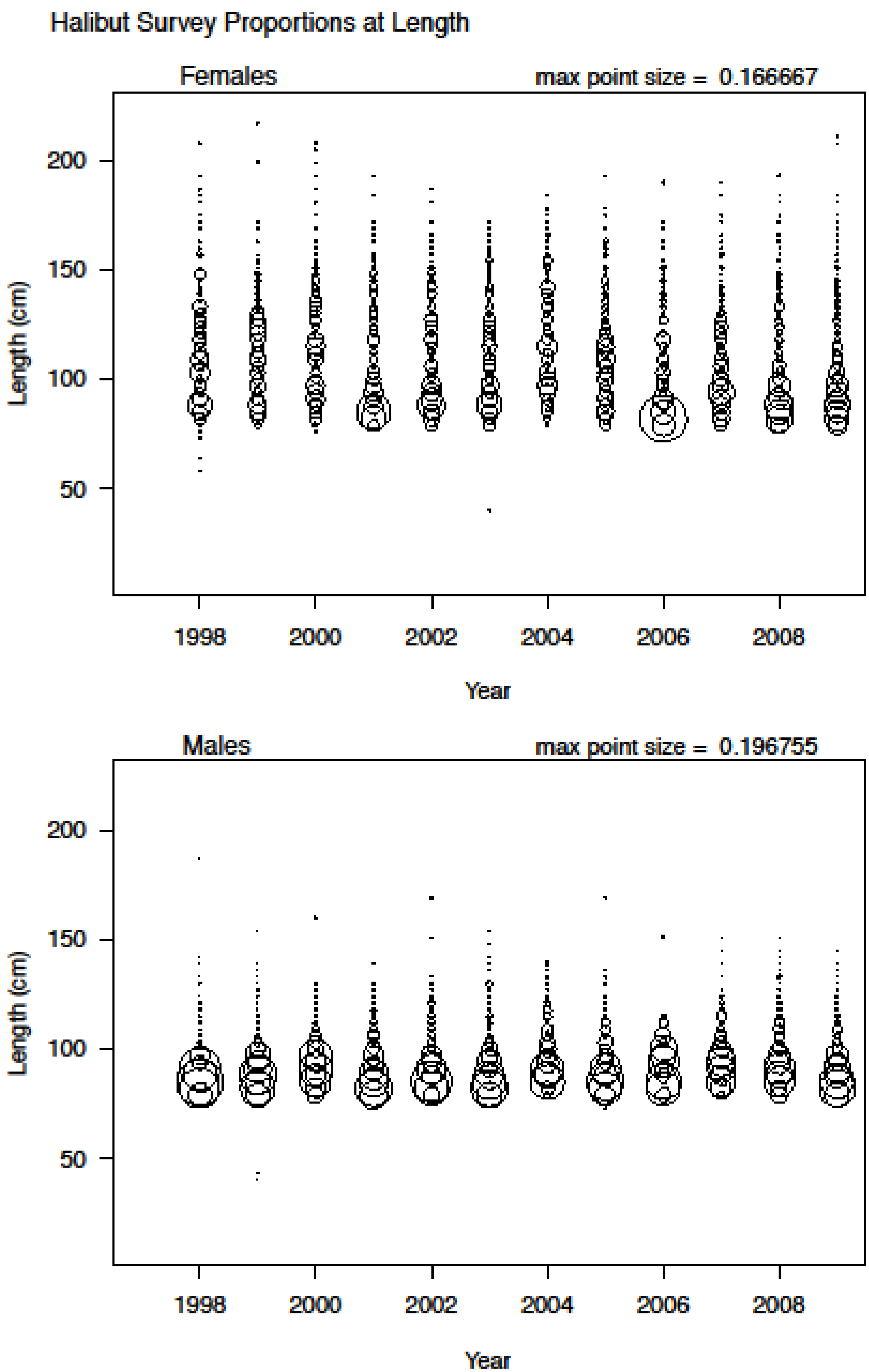

Otter trawl catch
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
1000s
Length (cm)


Otter trawl catch
2003
2004
2005
2006
2007
2008
2009
1000s
Length (cm)

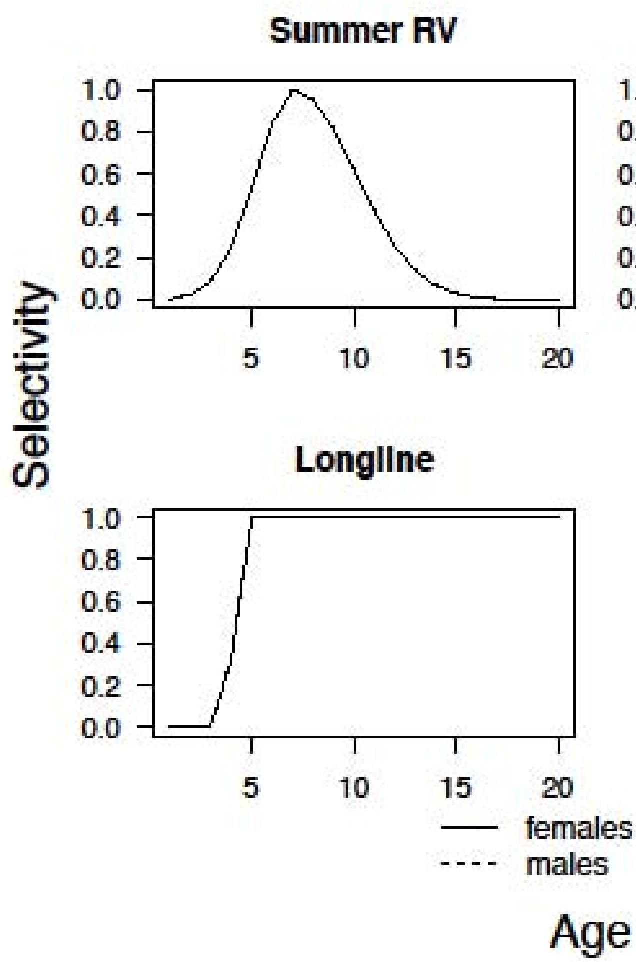

LL Proportions at Length
Females
Length (cm)
200
150
100
50
1990
1995
2000
2005
Year
Males
Length (cm)
200
150
100
50
1990
1995
2000
2005
Year

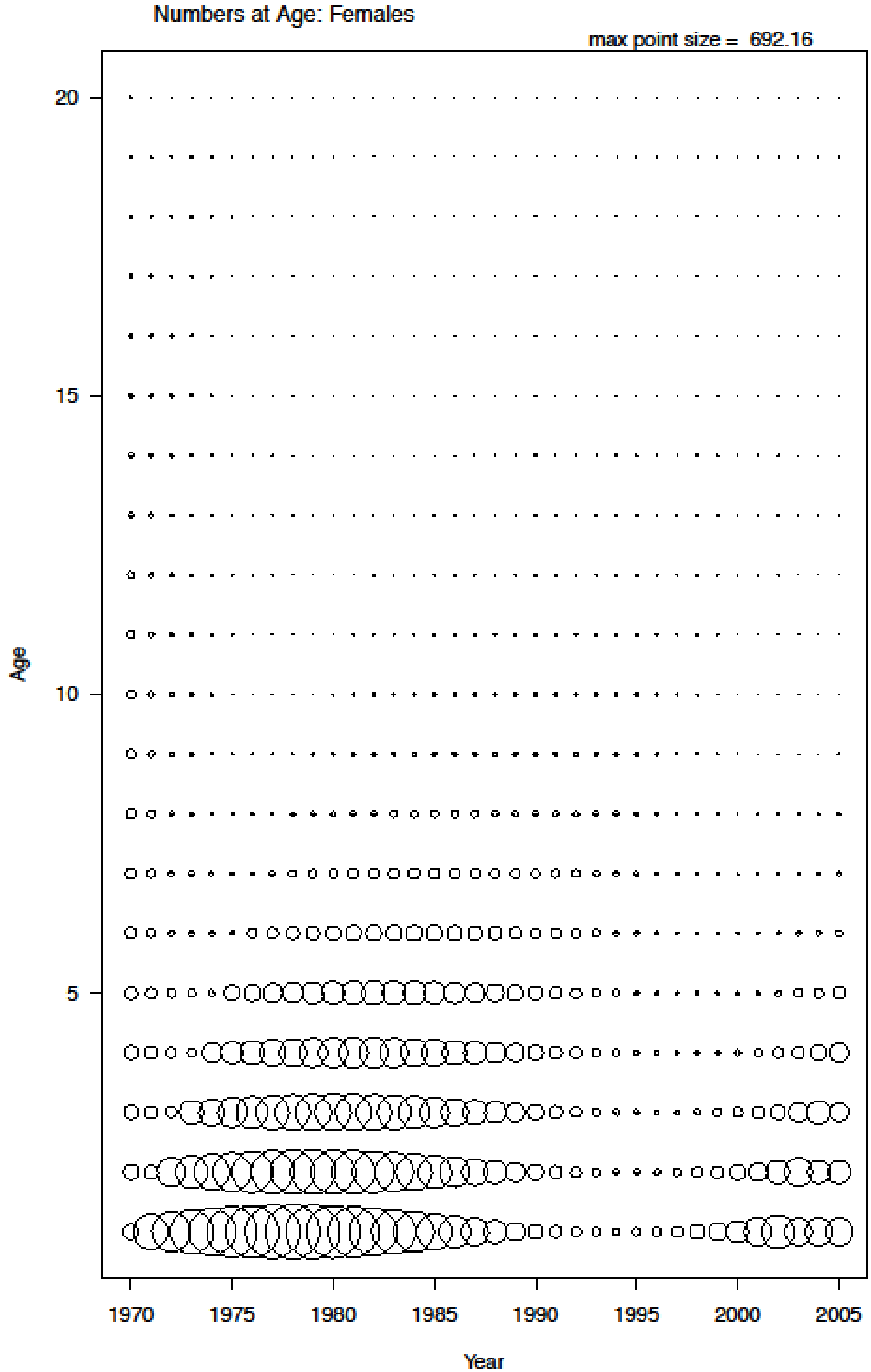

OT Proportions at Length
Females & Males
max point size = 0.259259
Length (cm)
200
150
100
50
1980
1985
1990
1995
2000
2005
2010
Year


Summer Survey Proportions at Length
Females
max point size = 0.299276
Length (cm)
200
150
100
50
1970
1980
1990
2000
2010
Year
Males
max point size = 0.402257
Length (cm)
200
150
100
50
1970
1980
1990
2000
2010
Year

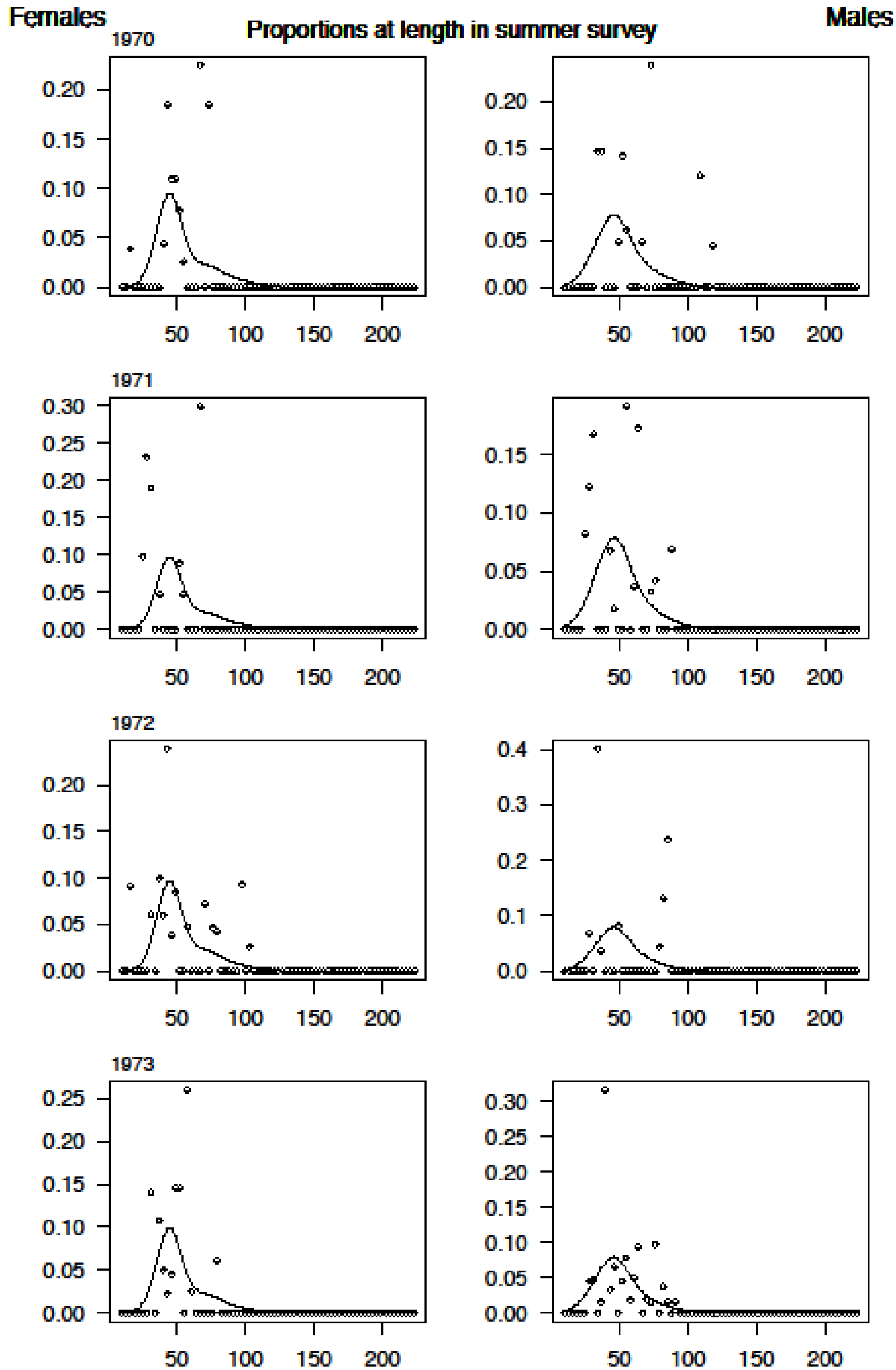

Halibut Survey Proportions at Length
Females
max point size = 0.166667
Length (cm)
200
150
100
50
1998
2000
2002
2004
2006
2008
Year
Males
max point size = 0.196755
Length (cm)
200
150
100
50
1998
2000
2002
2004
2006
2008
Year

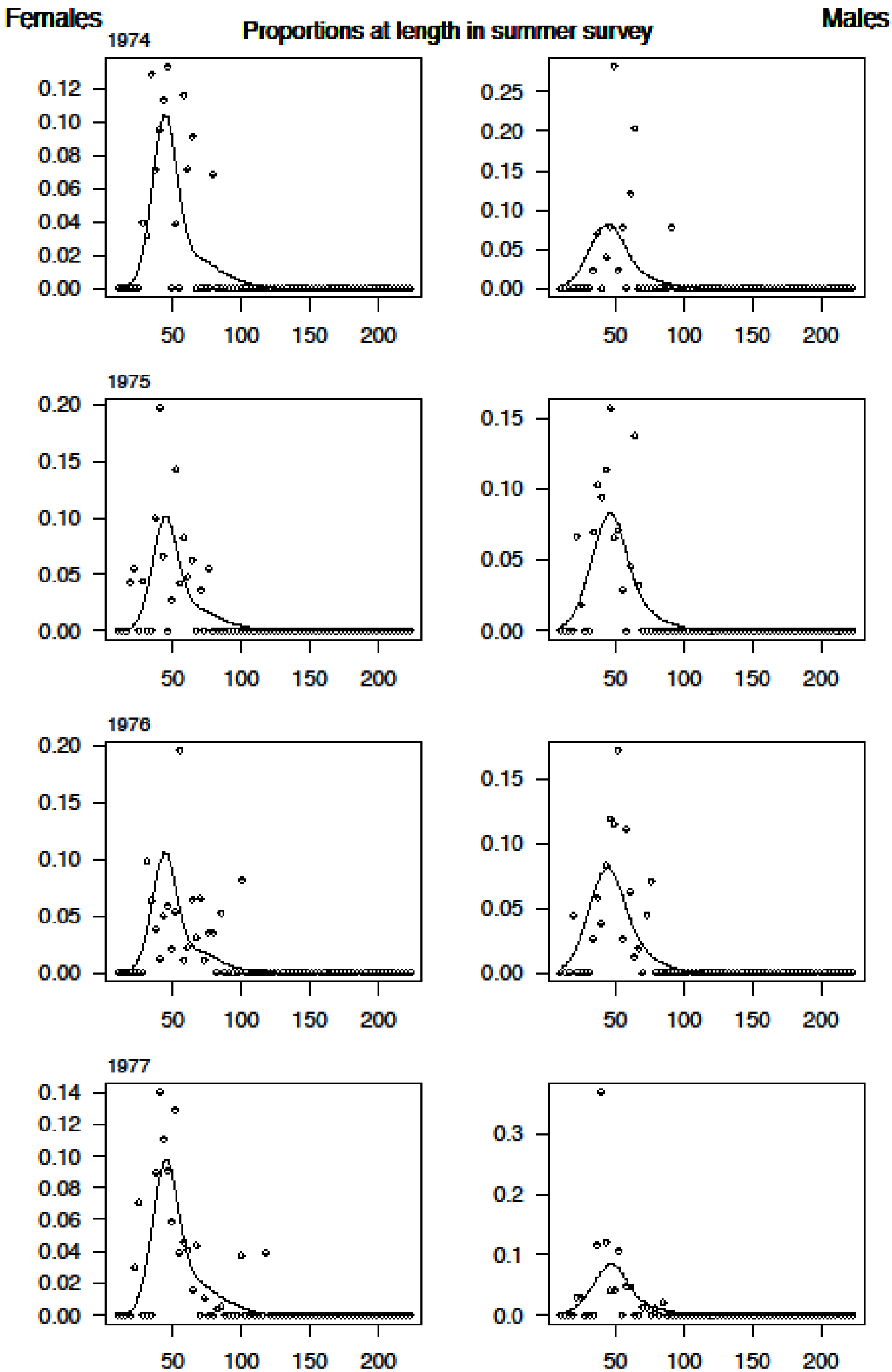
Appendix B. *Estimated selectivities and numbers at age used in the halibut simulation model.*

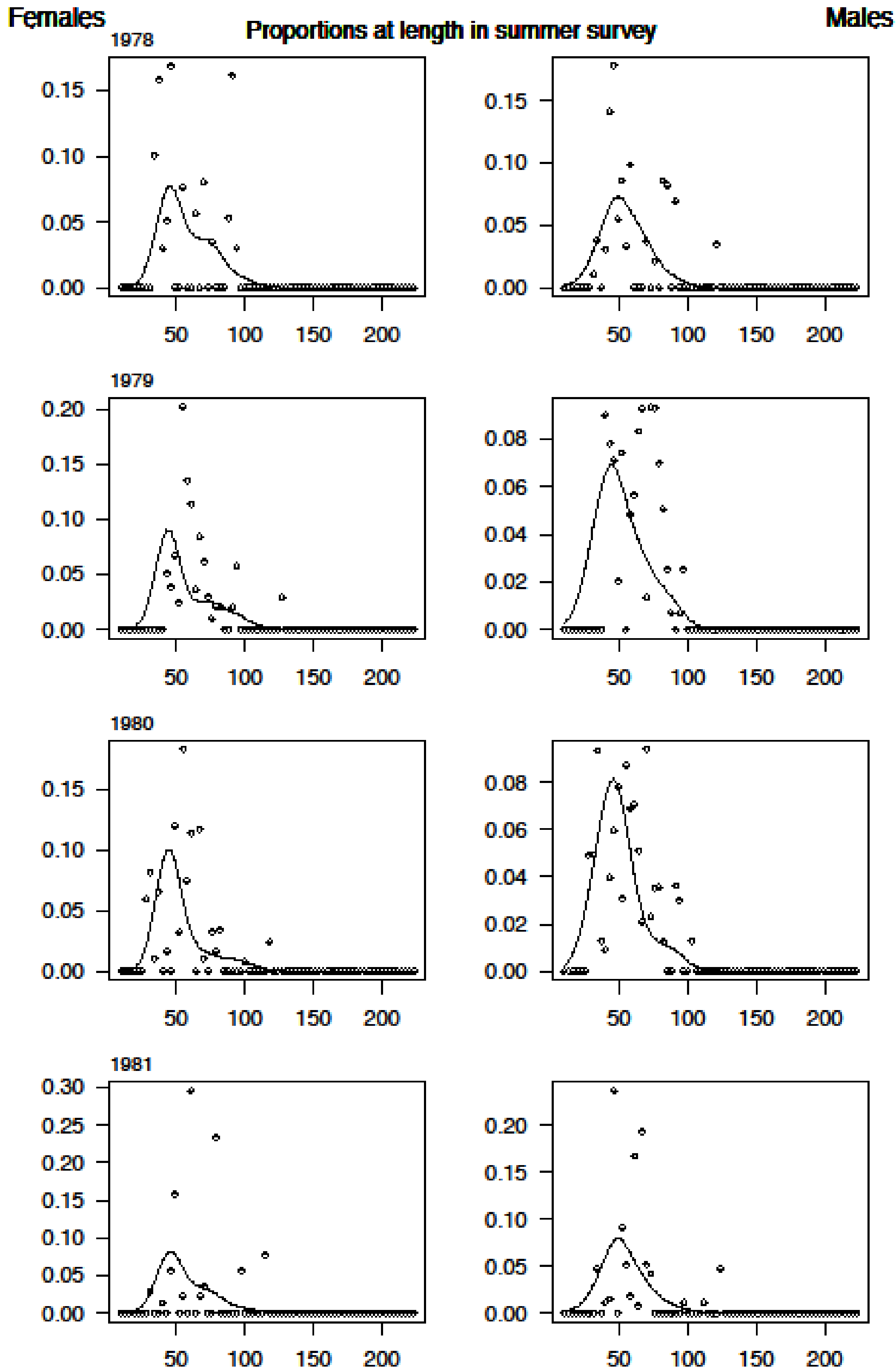


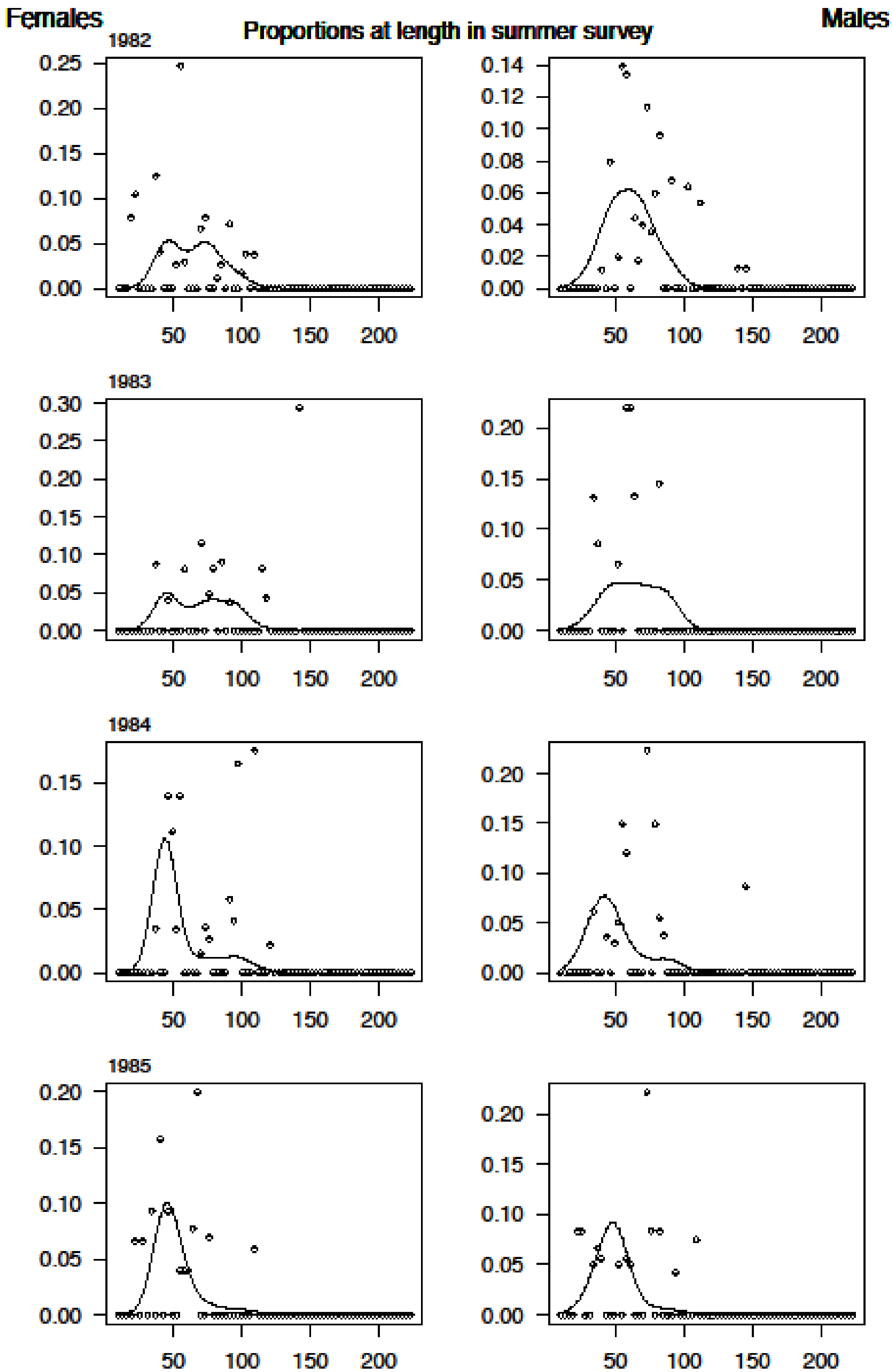

Numbers at Age: Females
max point size = 692.16
Age
Year
20
15
10
5
1970
1975
1980
1985
1990
1995
2000
2005

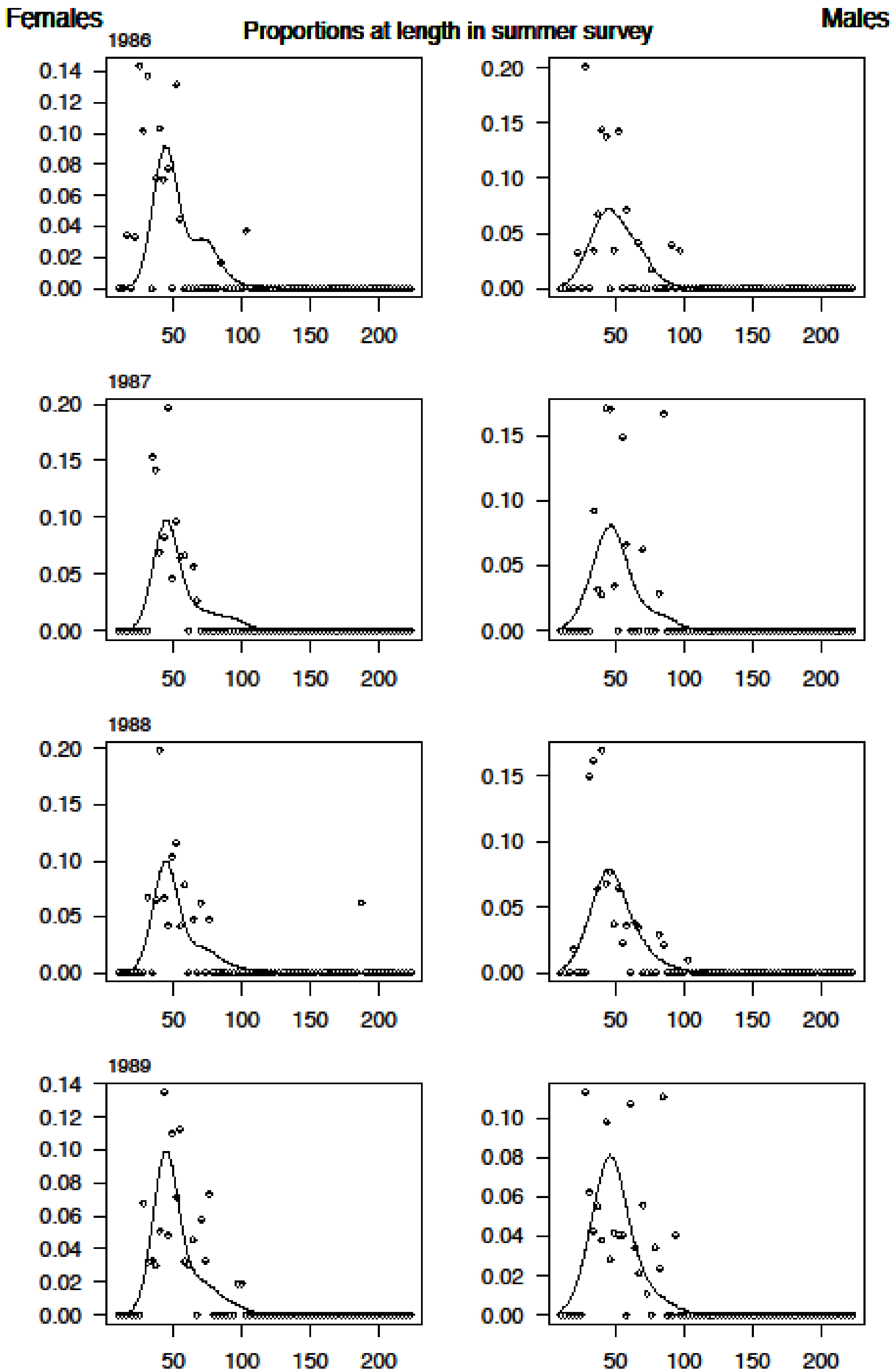
Appendix C. *Atlantic halibut proportions at length (points) and model fit (line) for each data component. Residual plots plotted against length and year.*

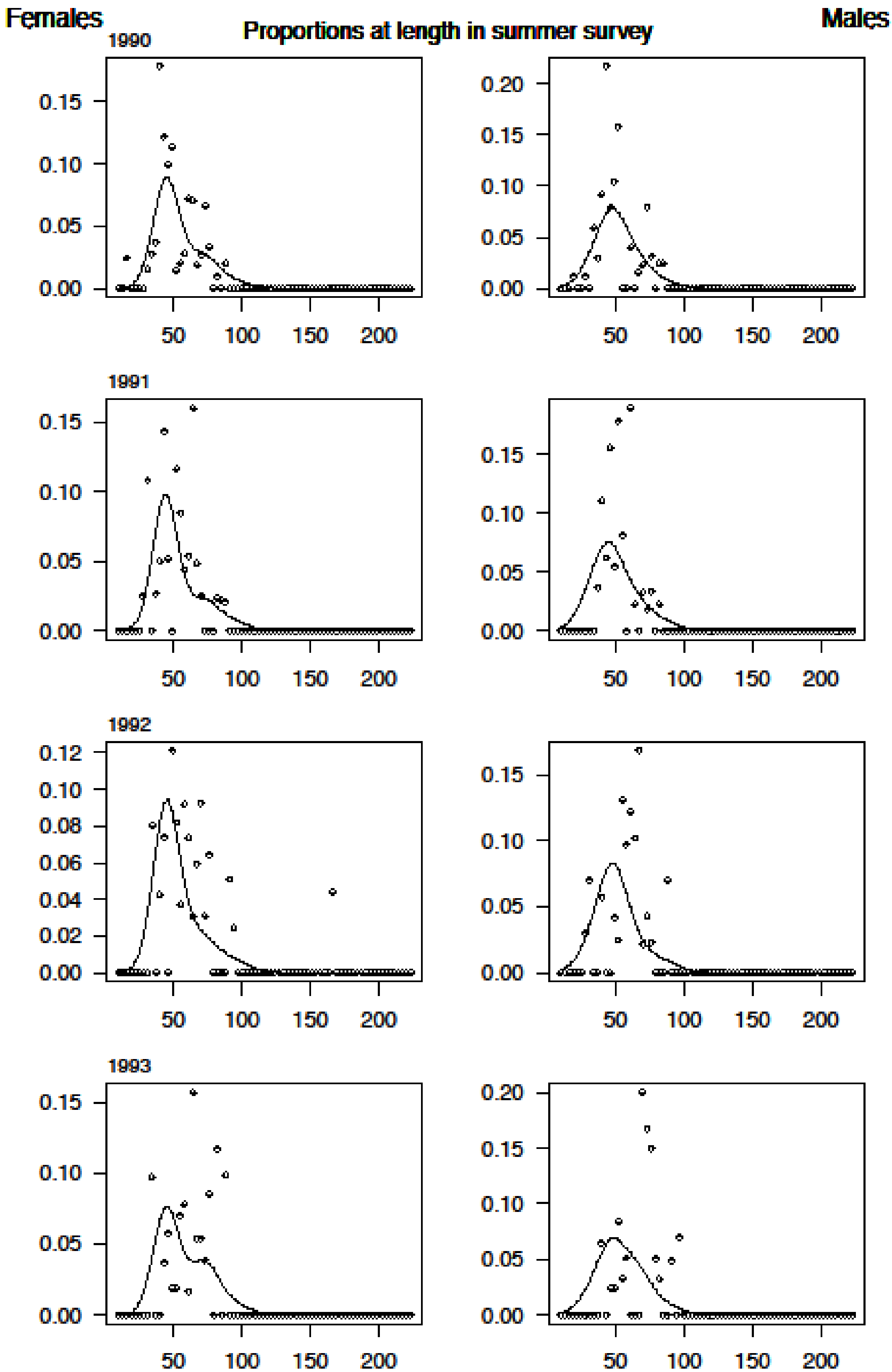


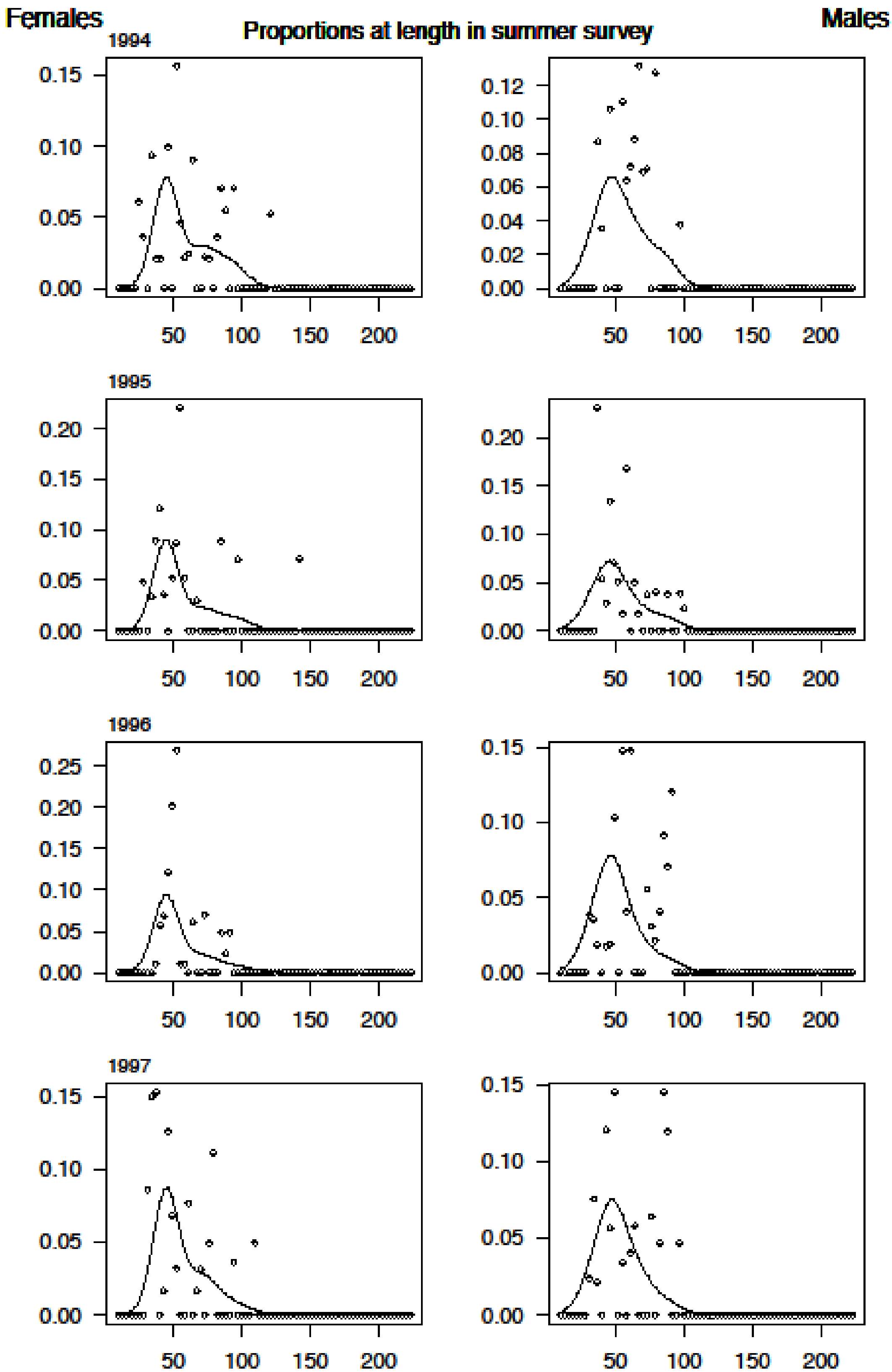

Females
Males
Proportions at length in summer survey
1974
1975
1976
1977
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.05
0.15
0.20
0.25
0.1
0.2
0.3
50
100
150
200


Females
Proportions at length in summer survey
Males
1978
1979
1980
1981
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.02
0.04
0.06
0.08
50
100
150
200

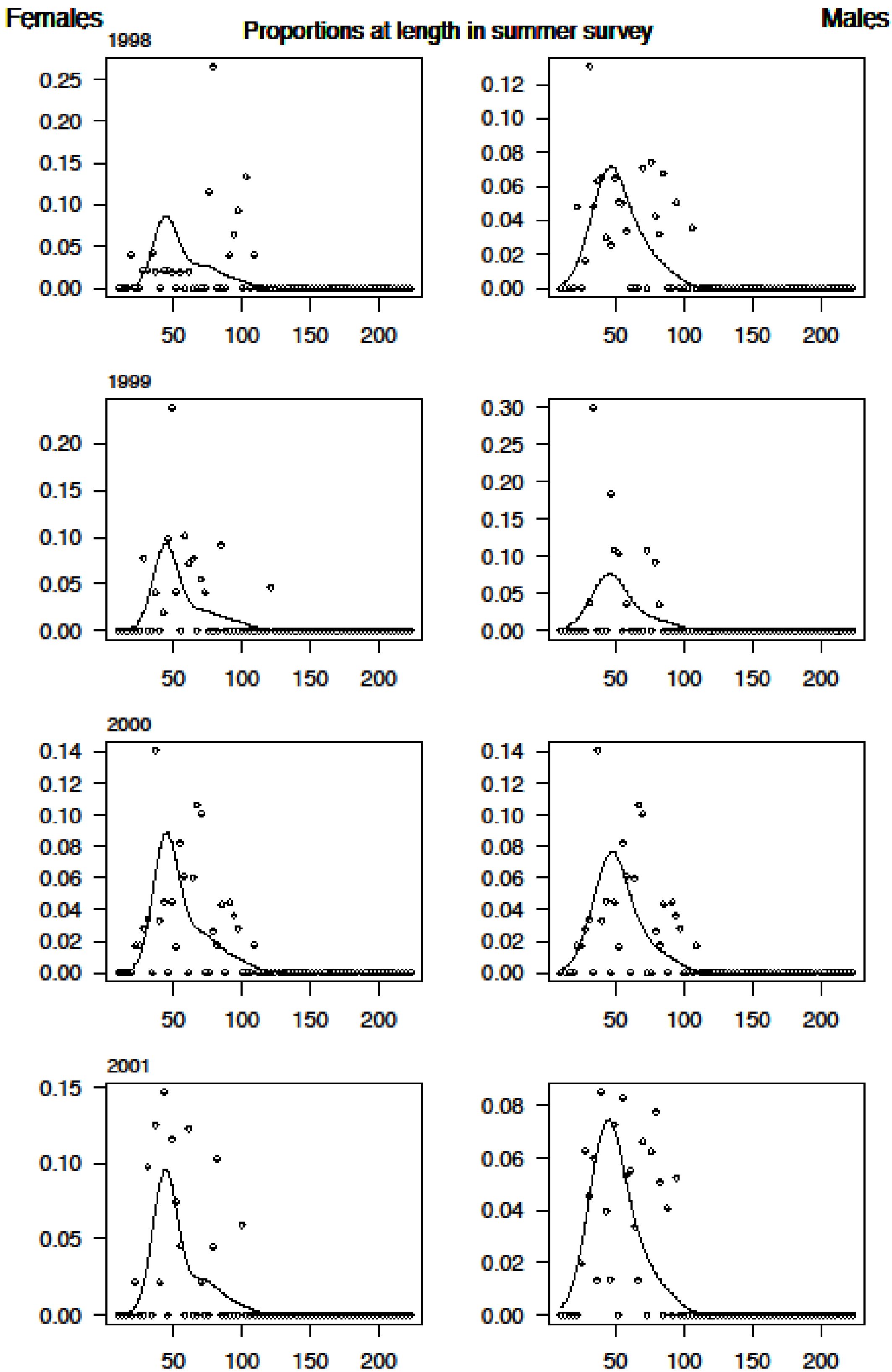

Females
Proportions at length in summer survey
Males
1982
1983
1984
1985

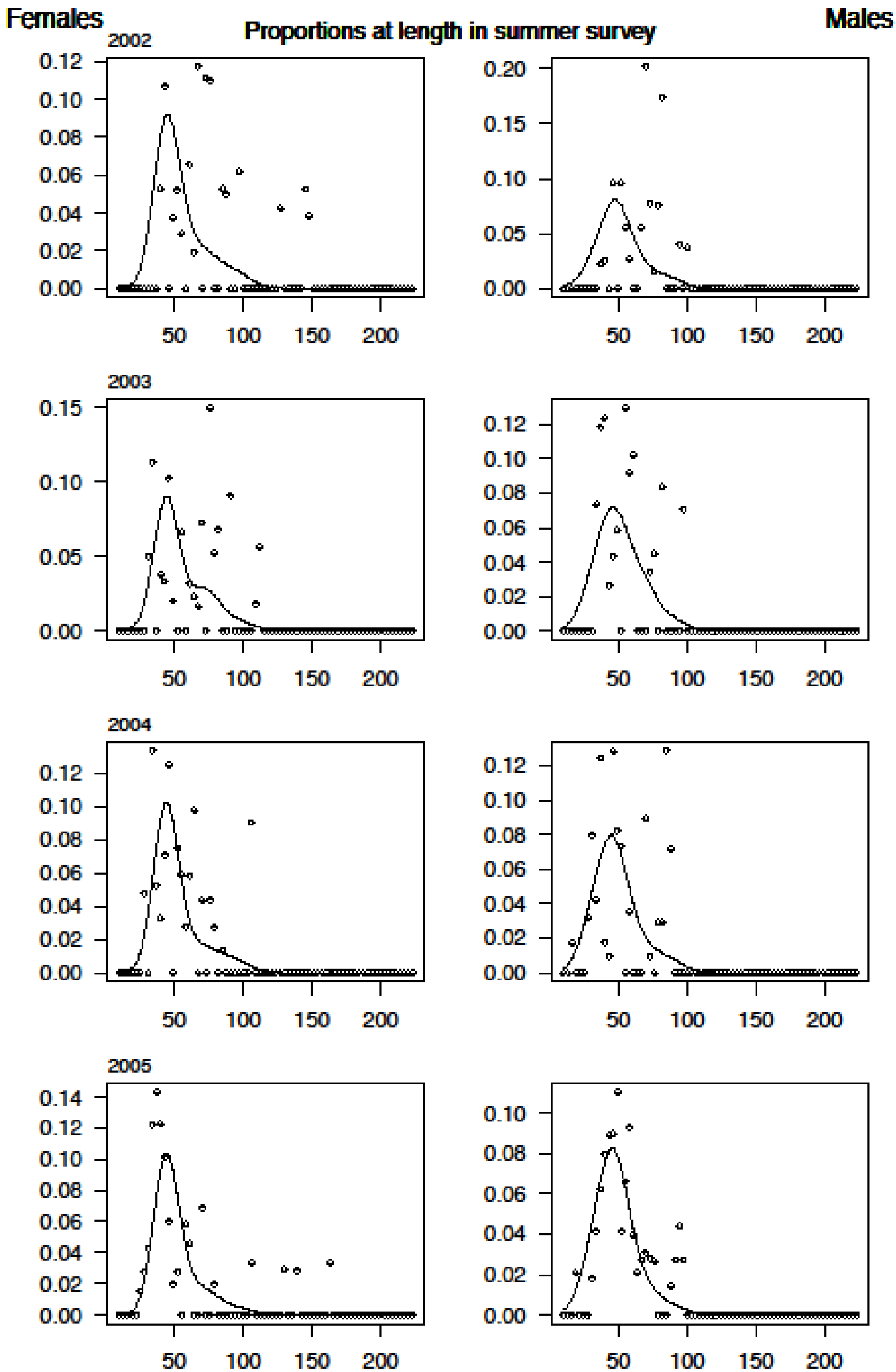

Females
Proportions at length in summer survey
Males
1986
1987
1988
1989
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.20
0.15
0.10
0.05
50
100
150
200

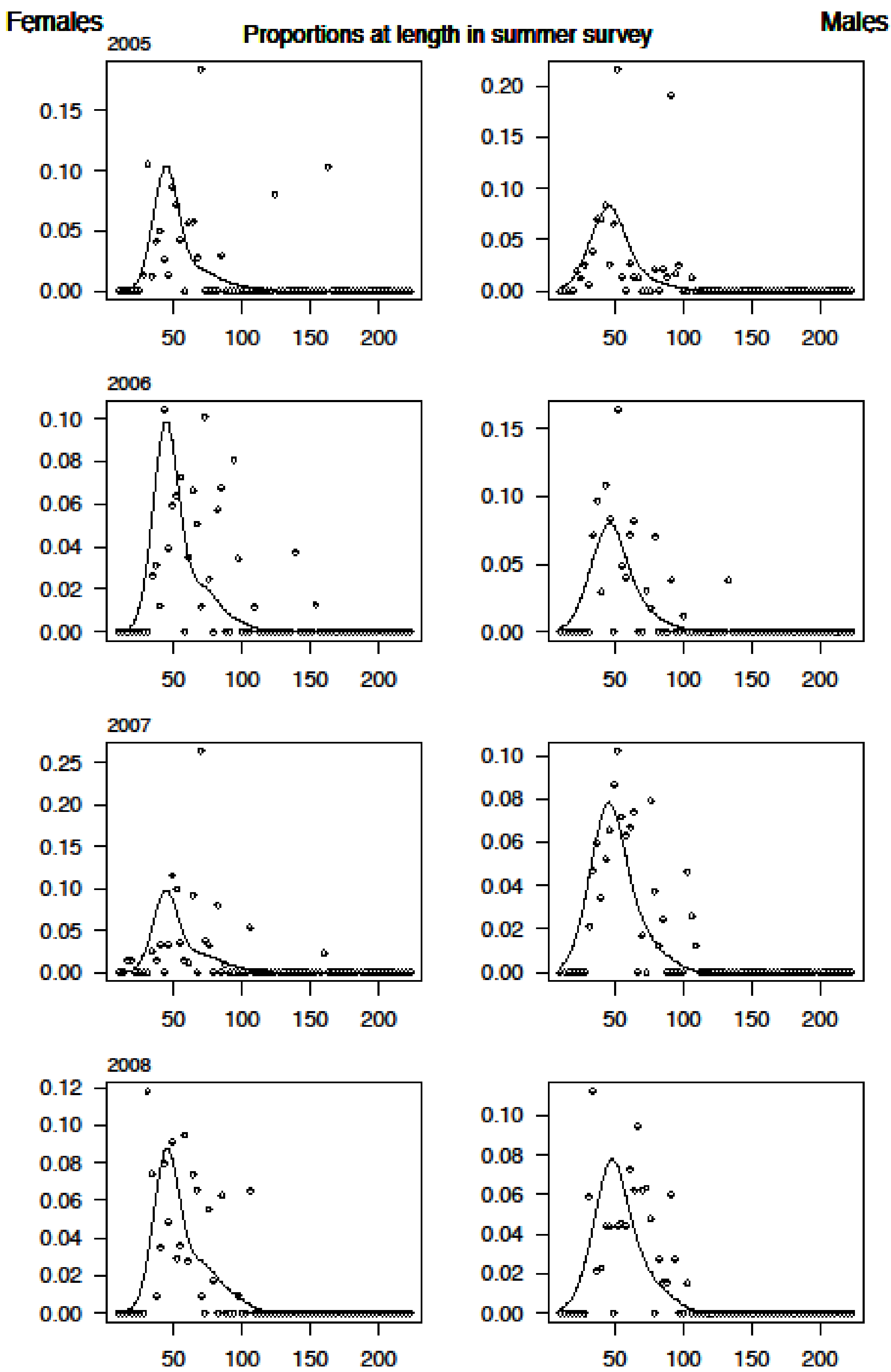

Females
Proportions at length in summer survey
Males
1990
1991
1992
1993

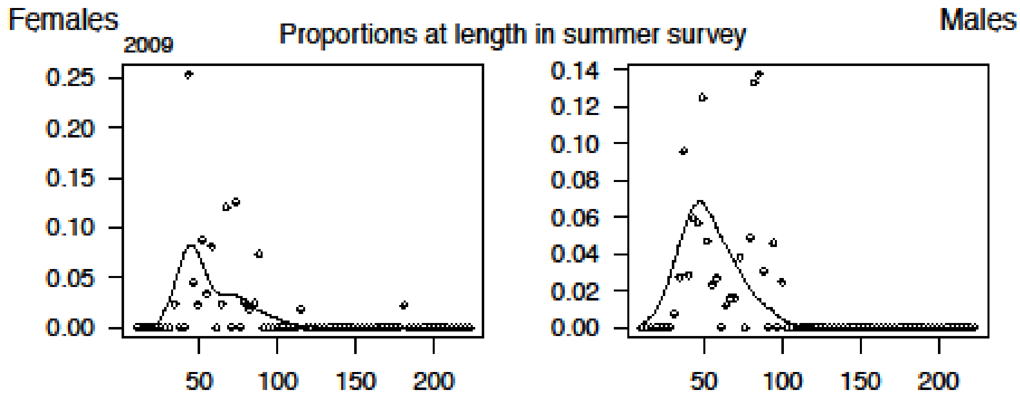


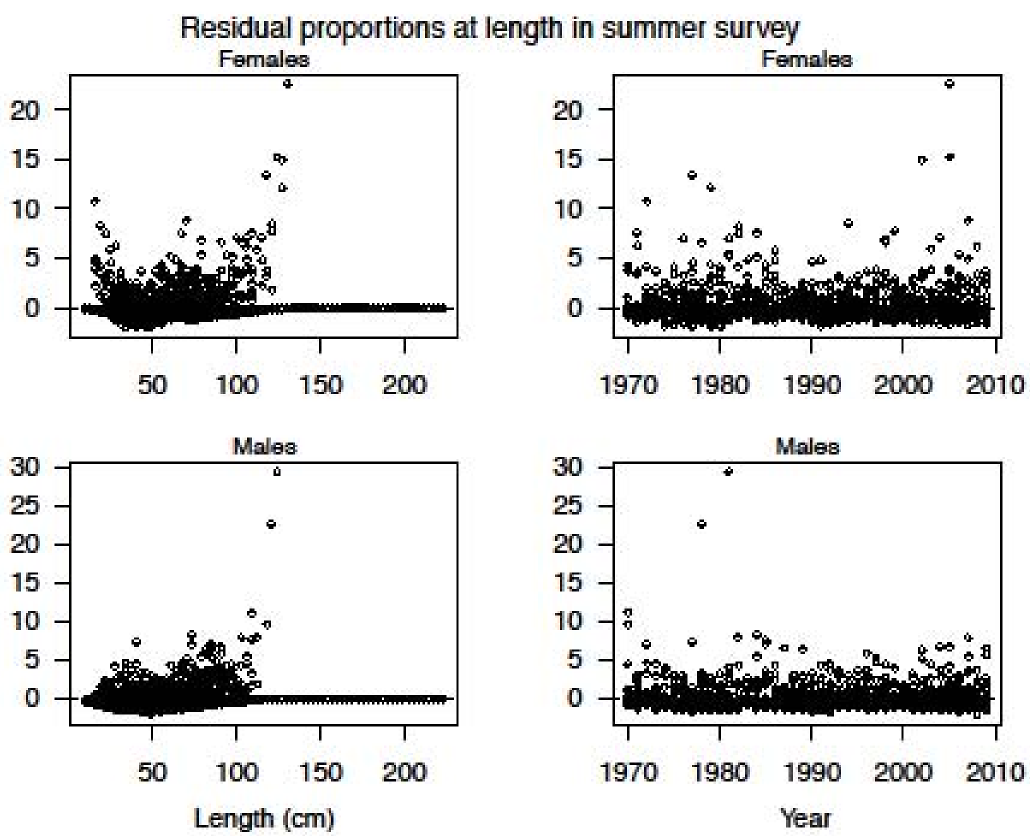
Females
Proportions at length in summer survey
Males
1994
1995
1996
1997
0.00
0.05
0.10
0.15
0.20
0.25
0.02
0.04
0.06
0.08
0.12
50
100
150
200

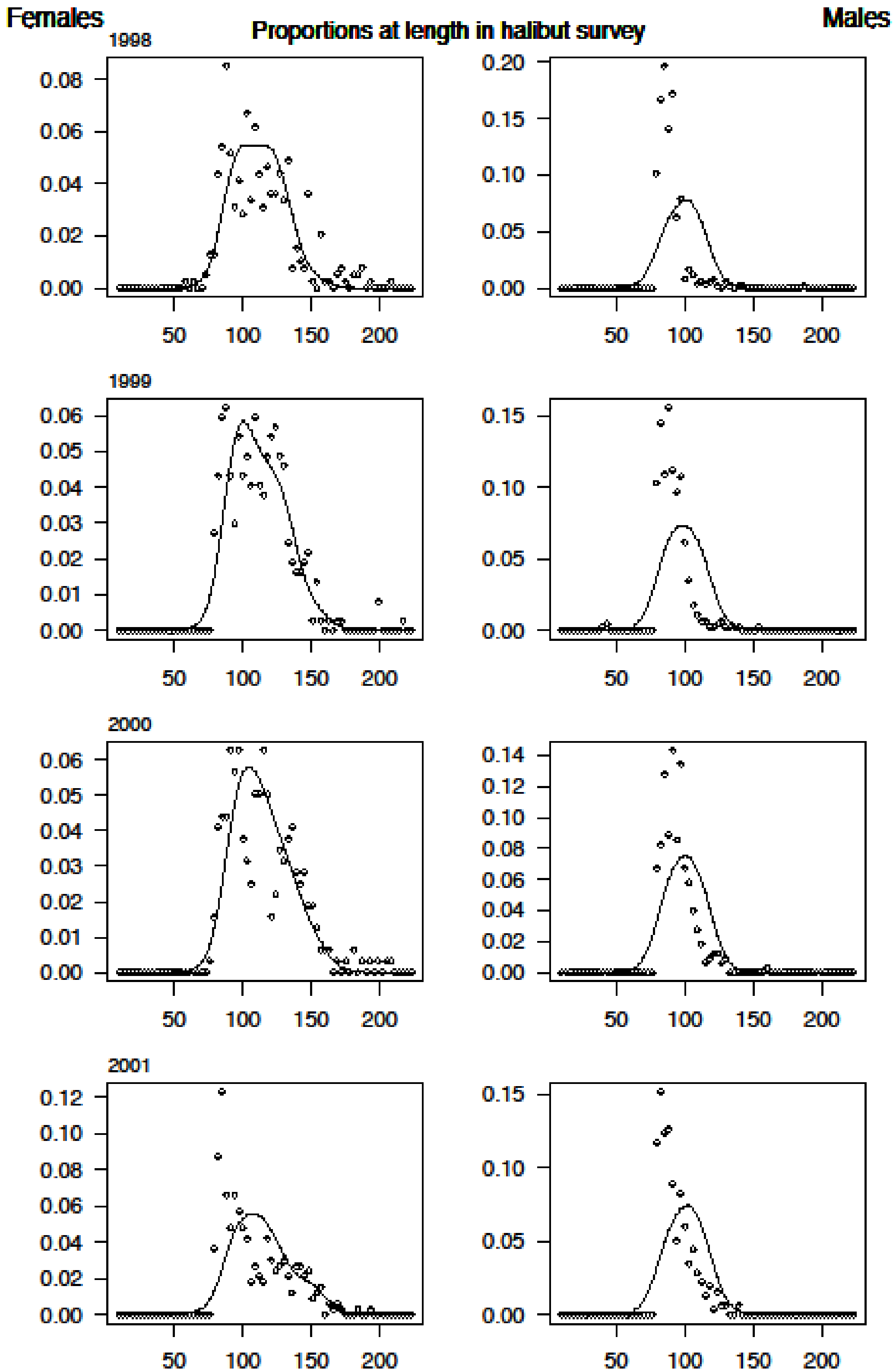

Females
Proportions at length in summer survey
Males
1998
1999
2000
2001
0.25
0.20
0.15
0.10
0.05
0.00
0.12
0.08
0.06
0.04
0.02
0.30
0.14
50
100
150
200

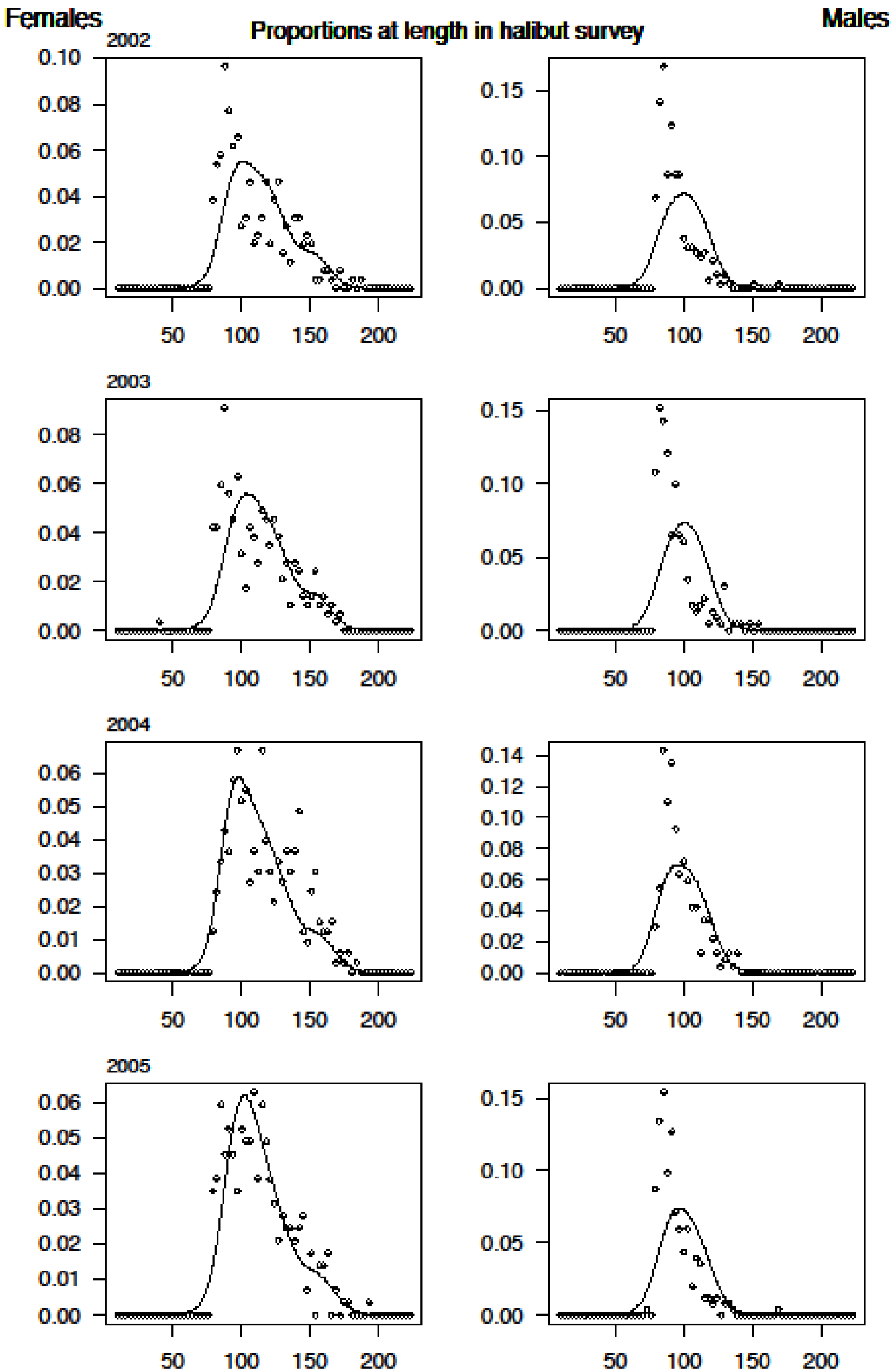

Females
Proportions at length in summer survey
Males
2002
2003
2004
2005
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.15
0.05
0.20
50
100
150
200

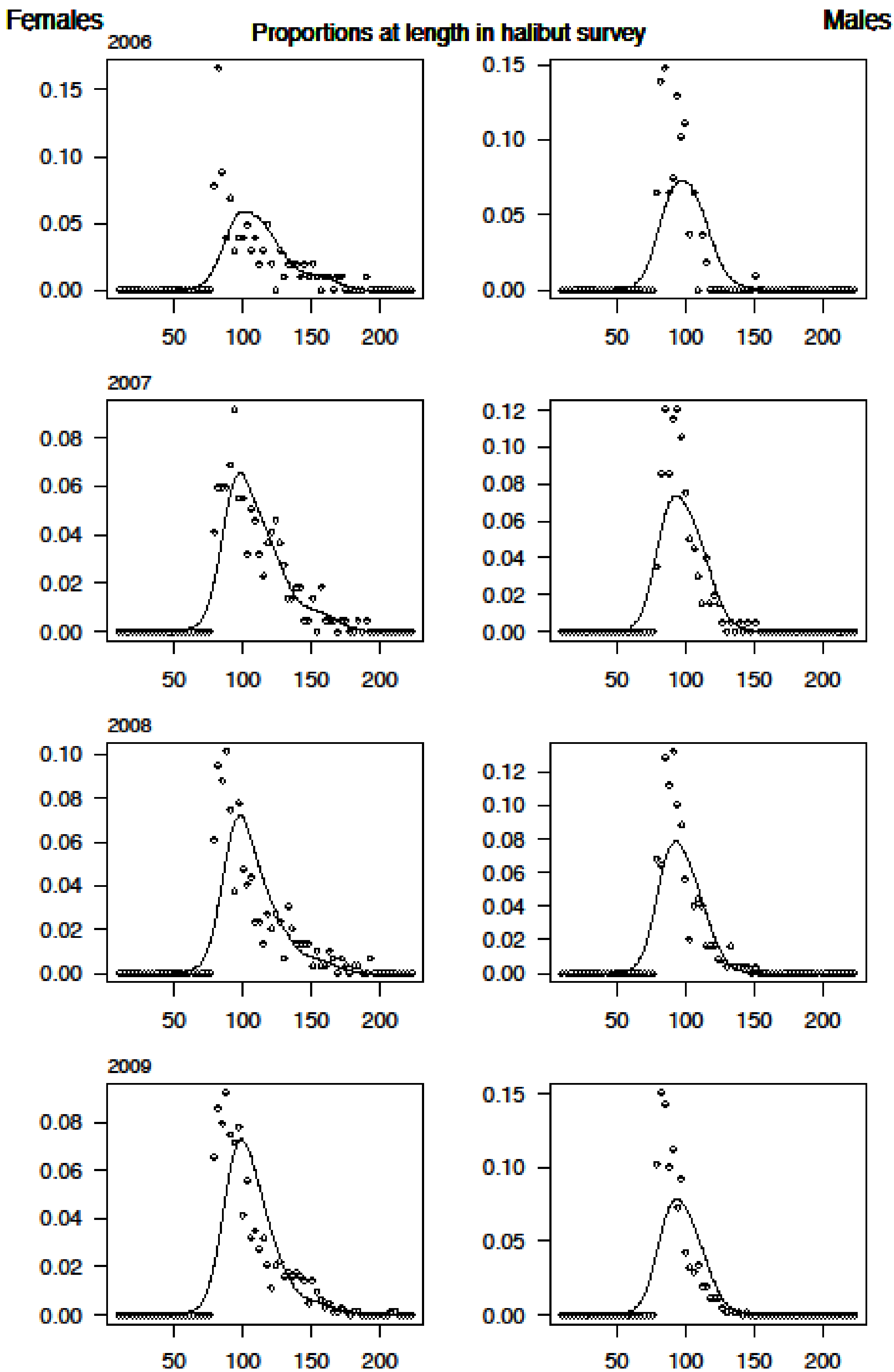

Females
Proportions at length in summer survey
Males
2005
2006
2007
2008
0.00
0.05
0.10
0.15
0.20
0.25
0.02
0.04
0.06
0.08
0.12
50
100
150
200

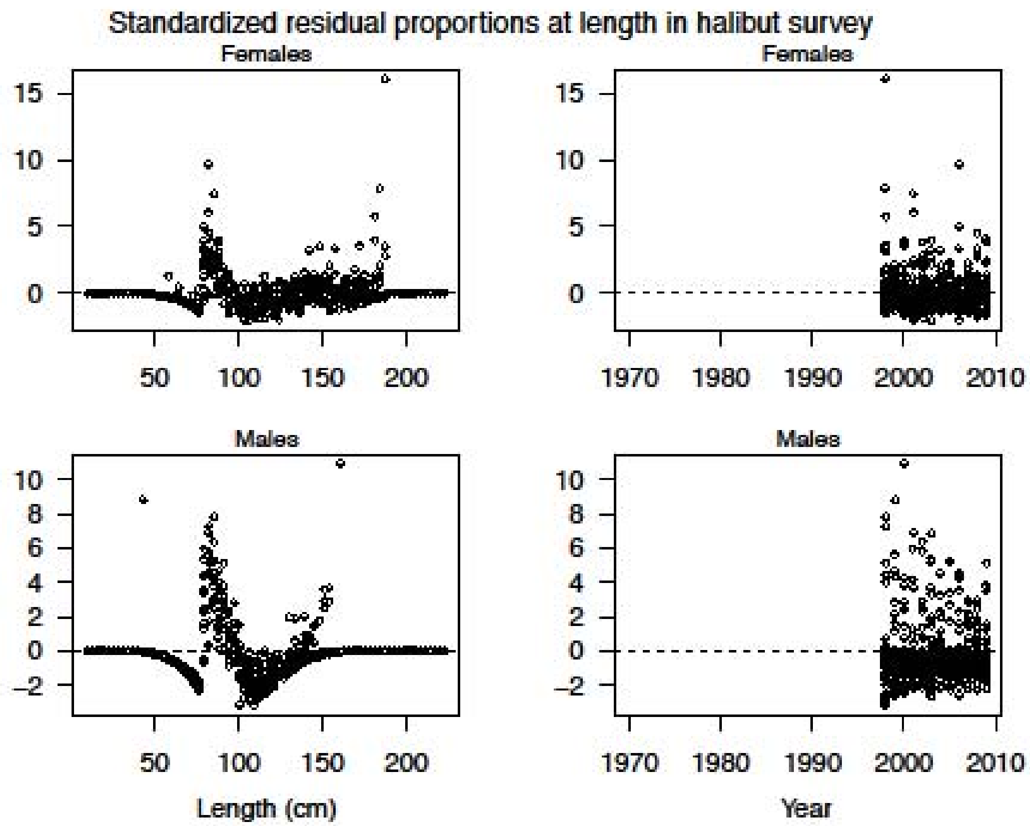

Females
2009
Proportions at length in summer survey
Males
0.25
0.20
0.15
0.10
0.05
0.00
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
50
100
150
200

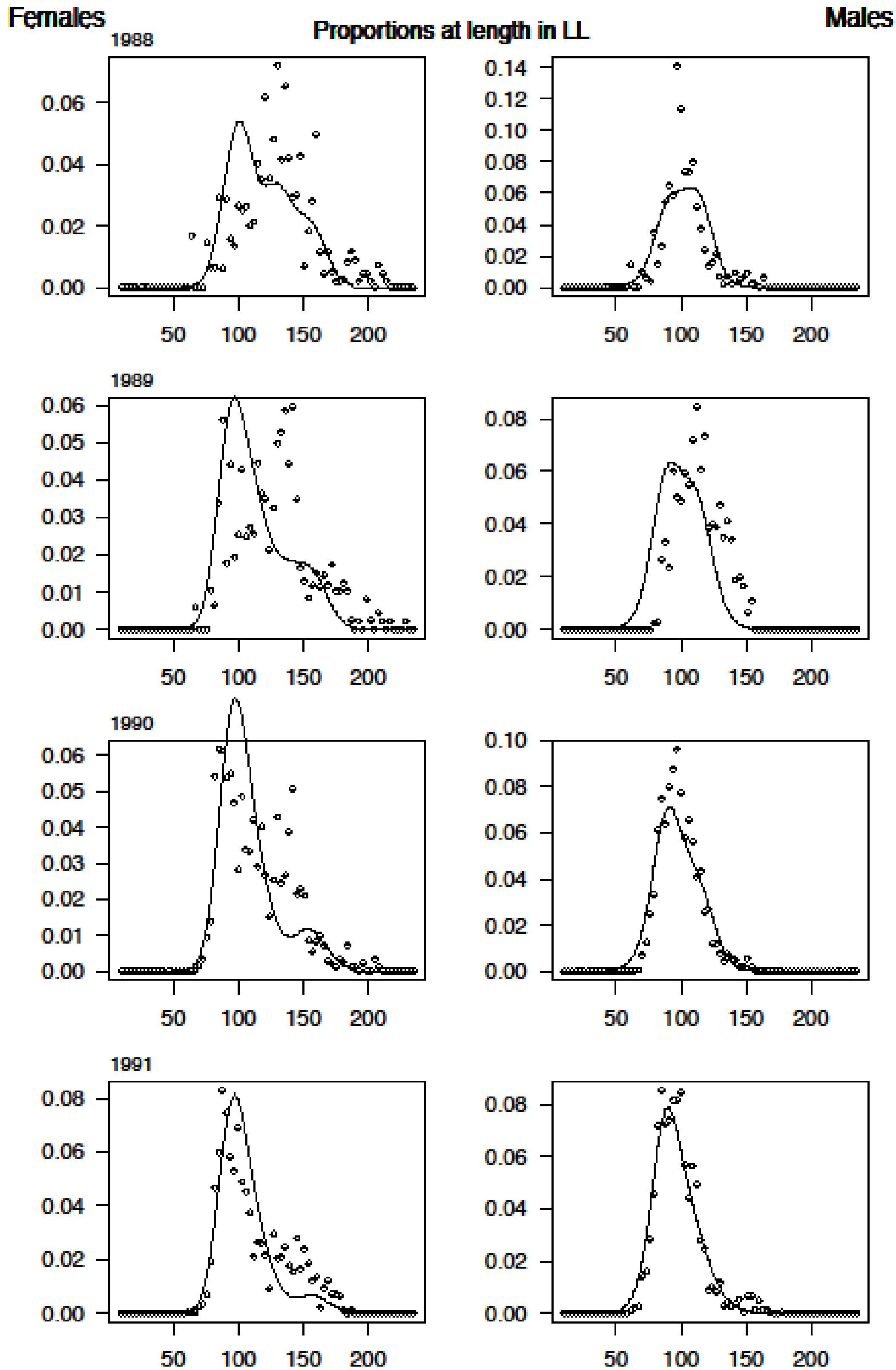

Residual proportions at length in summer survey
Females
Females
Males
Males
20
15
10
5
0
30
25
1970
1980
1990
2000
2010
50
100
150
200
Length (cm)
Year

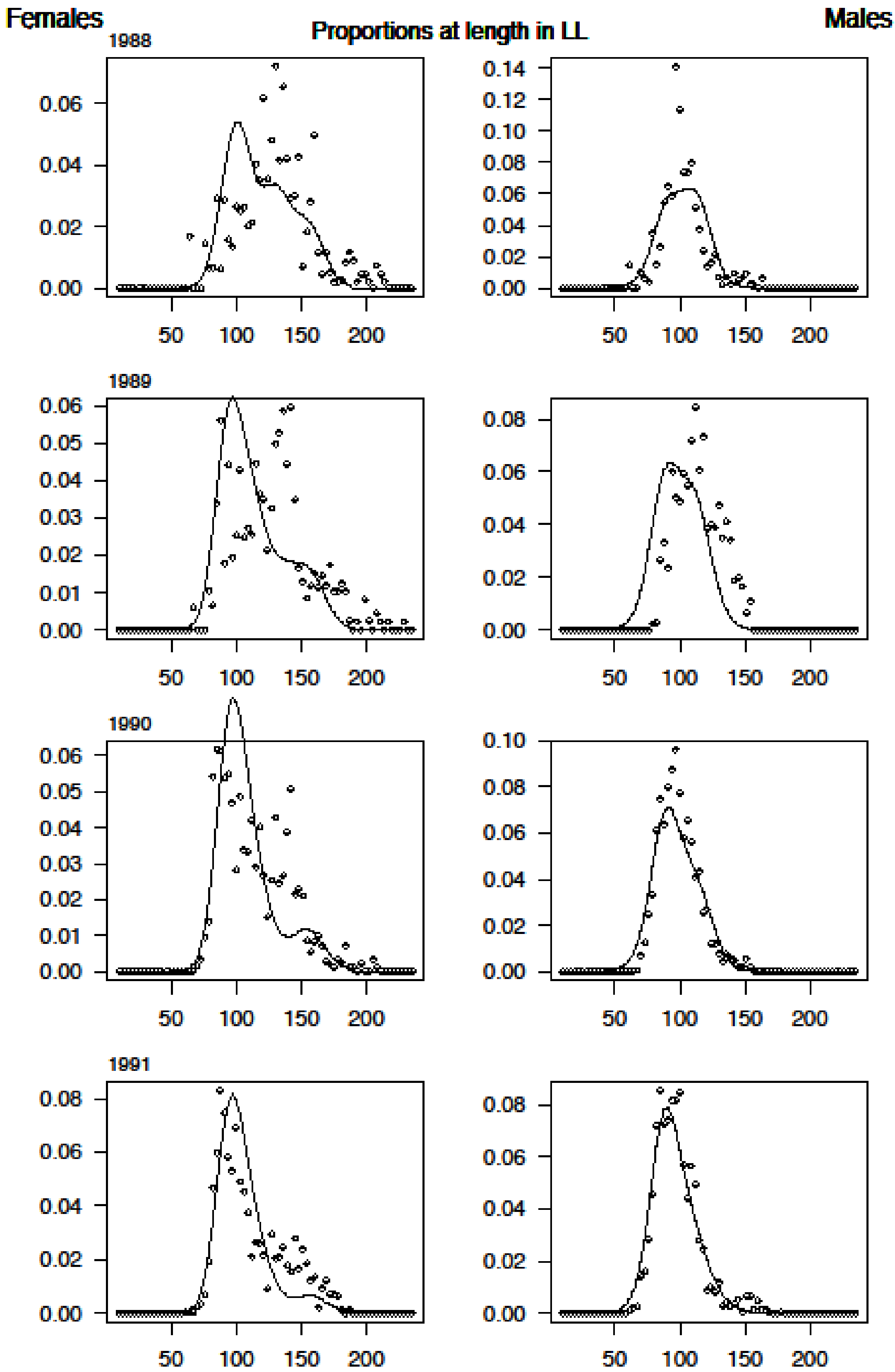

Females
Proportions at length in halibut survey
Males
1998
1999
2000
2001

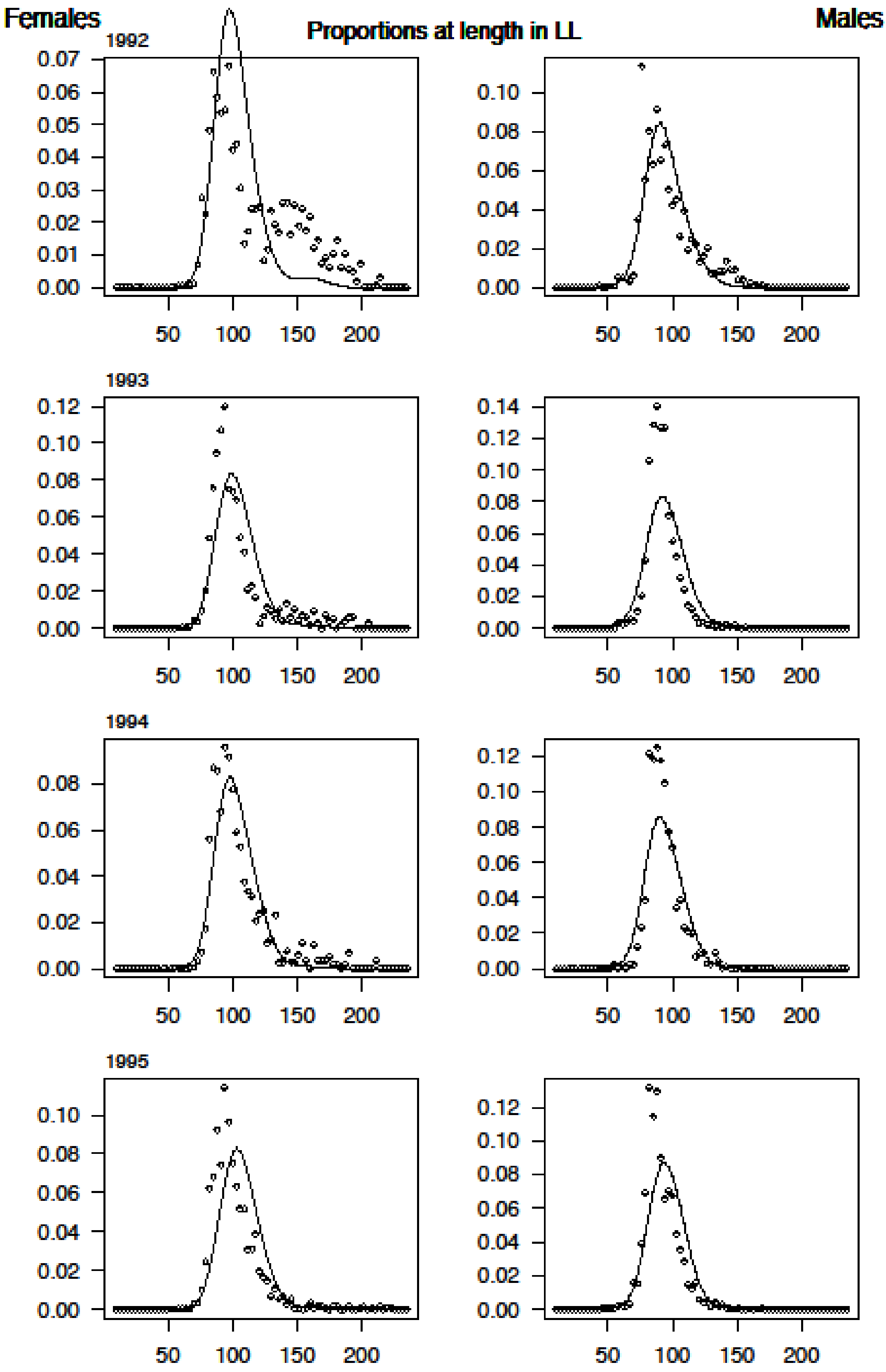

Females
Males
Proportions at length in halibut survey
2002
2003
2004
2005
0.10
0.08
0.06
0.04
0.02
0.00
0.15
0.10
0.05
0.14
0.12
0.05
0.03
0.01
50
100
150
200

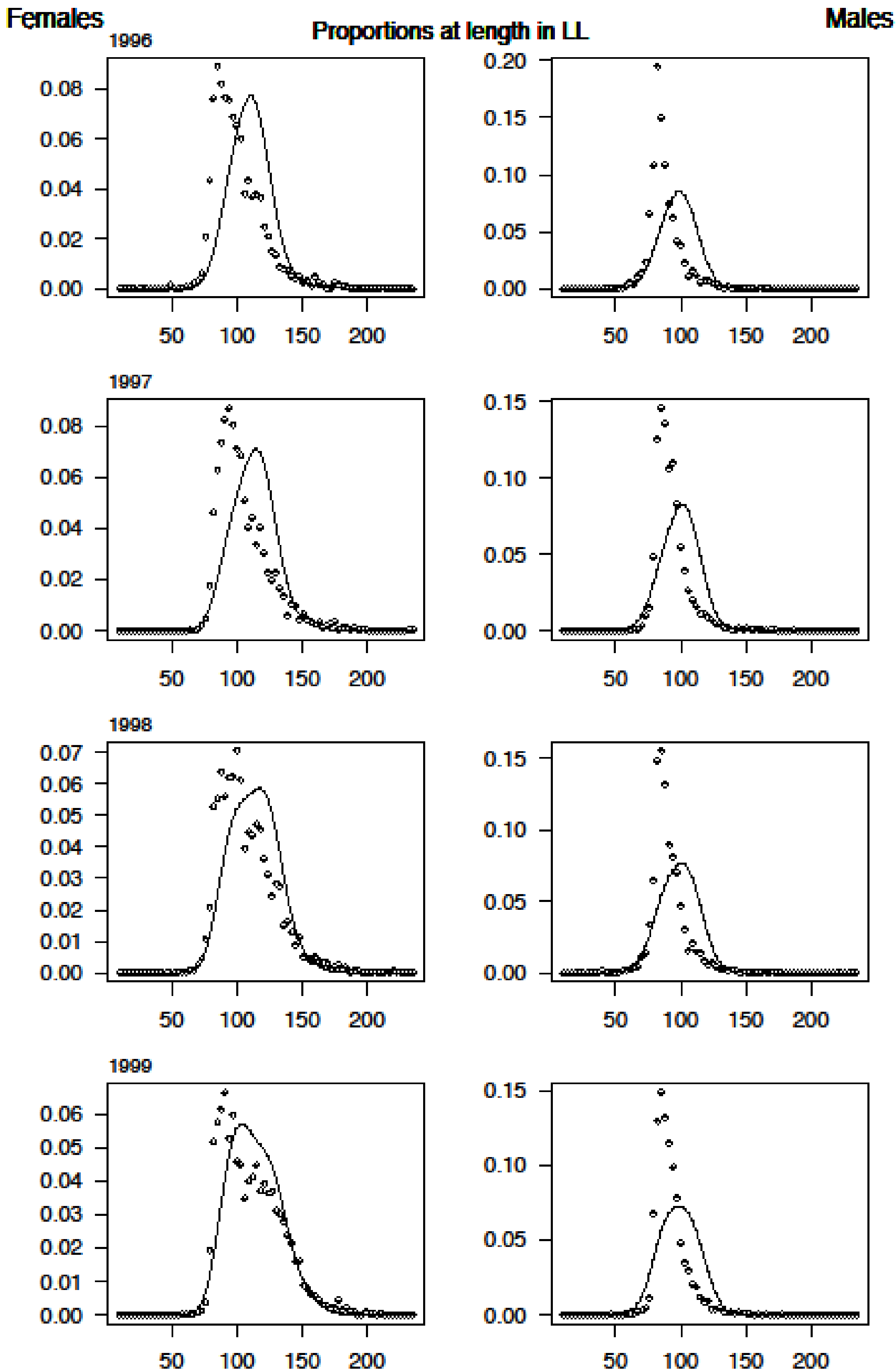

Females
Males
Proportions at length in halibut survey
2006
2007
2008
2009

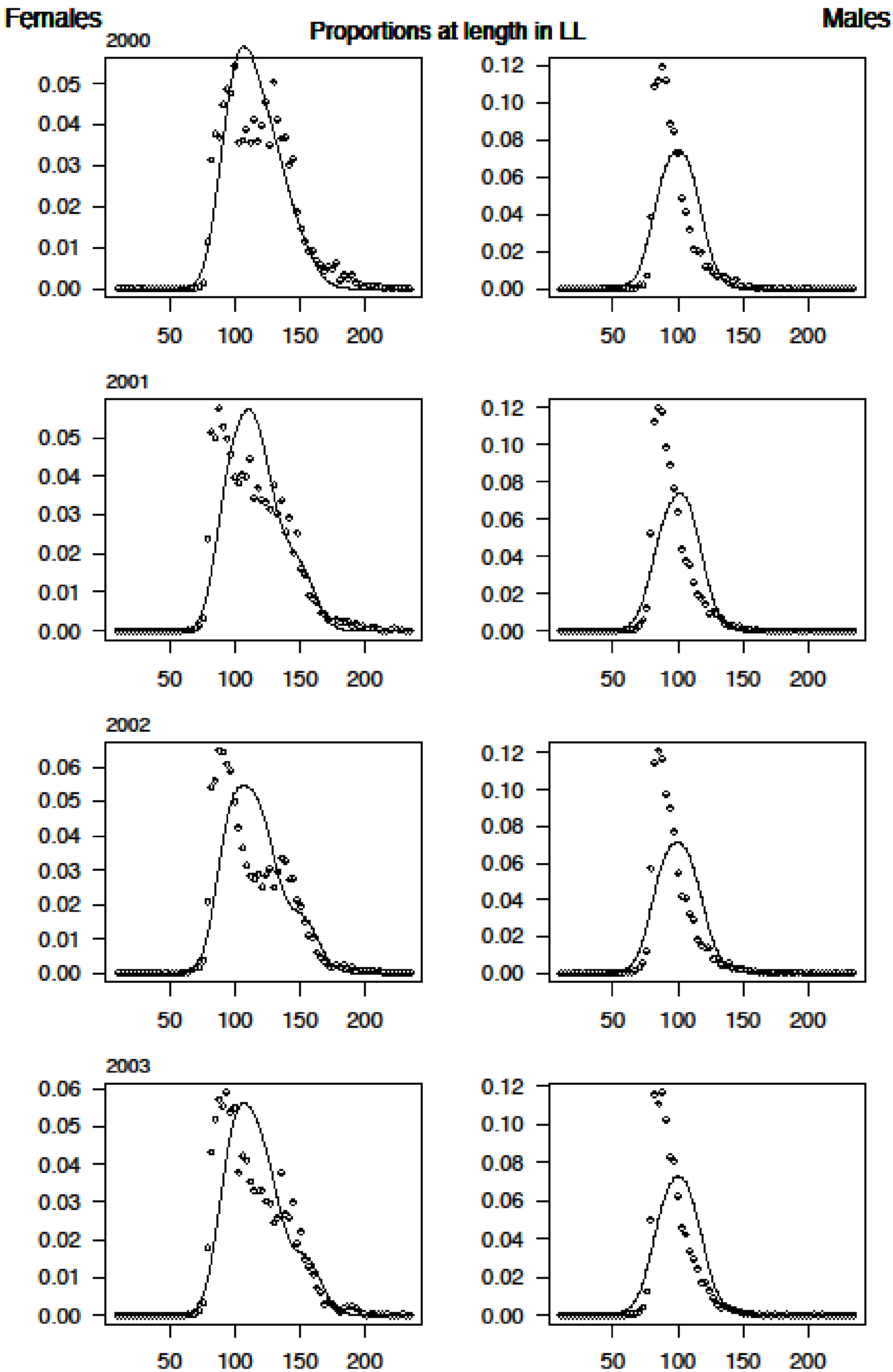

Standardized residual proportions at length in halibut survey
Females
Females
Males
Males
Length (cm)
Year
15
10
5
0
50
100
150
200
1970
1980
1990
2000
2010
8
6
4
2
–2

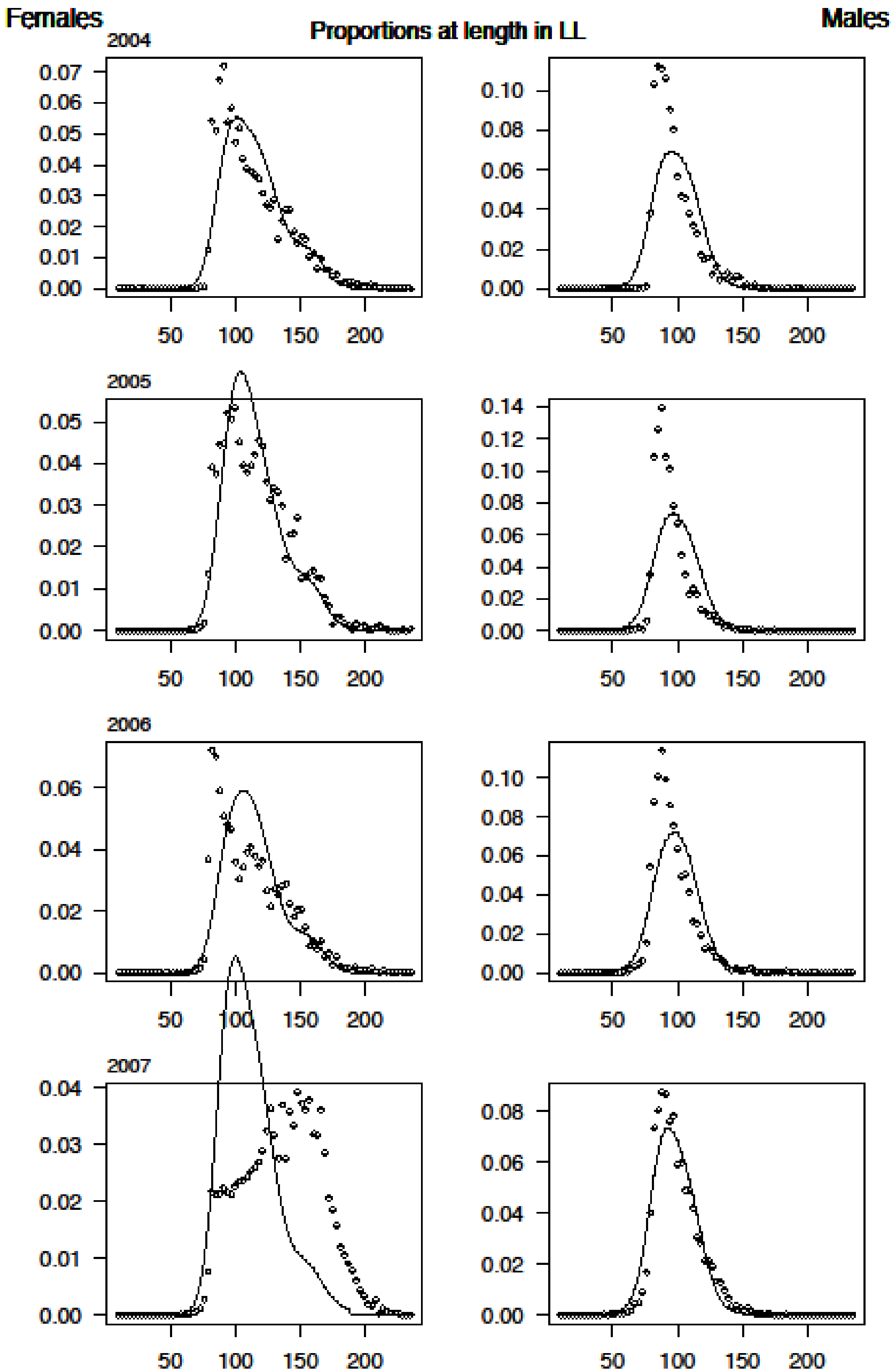

Females
Proportions at length in LL
Males
1988
1989
1990
1991
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.08
0.10
0.12
0.14
50
100
150
200

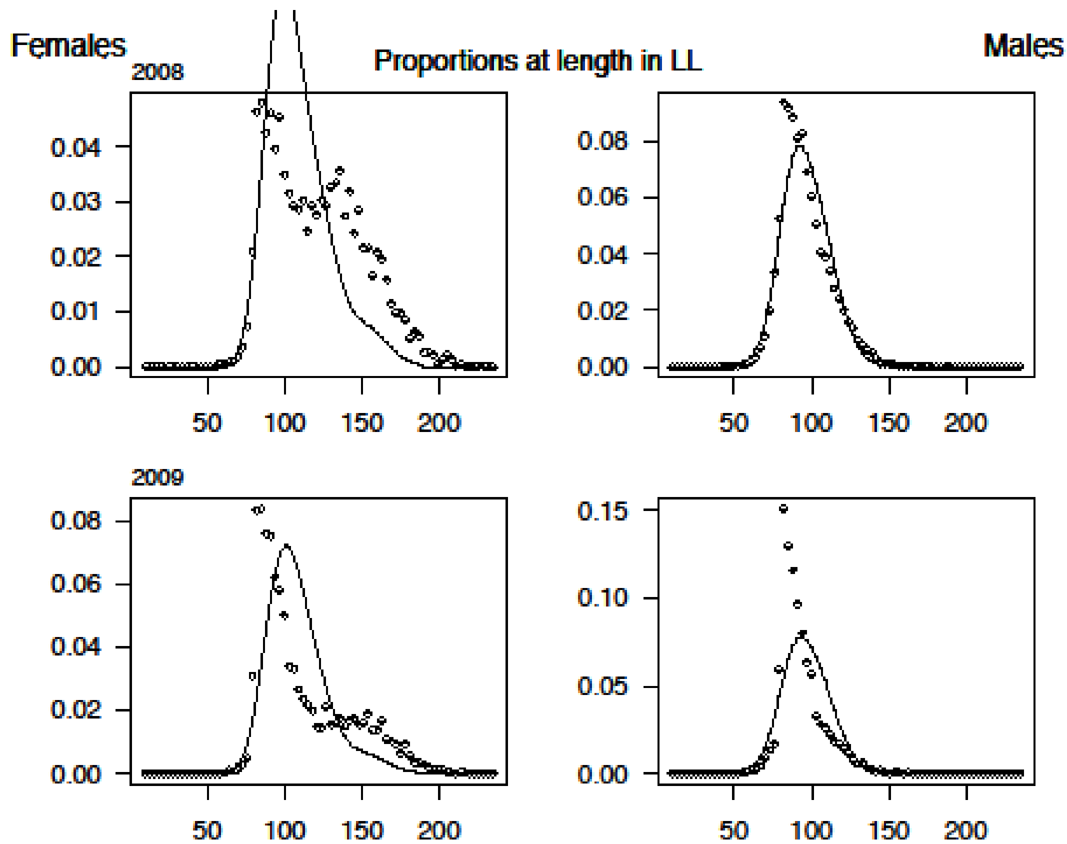

Females
Proportions at length in LL
Males
1988
1989
1990
1991

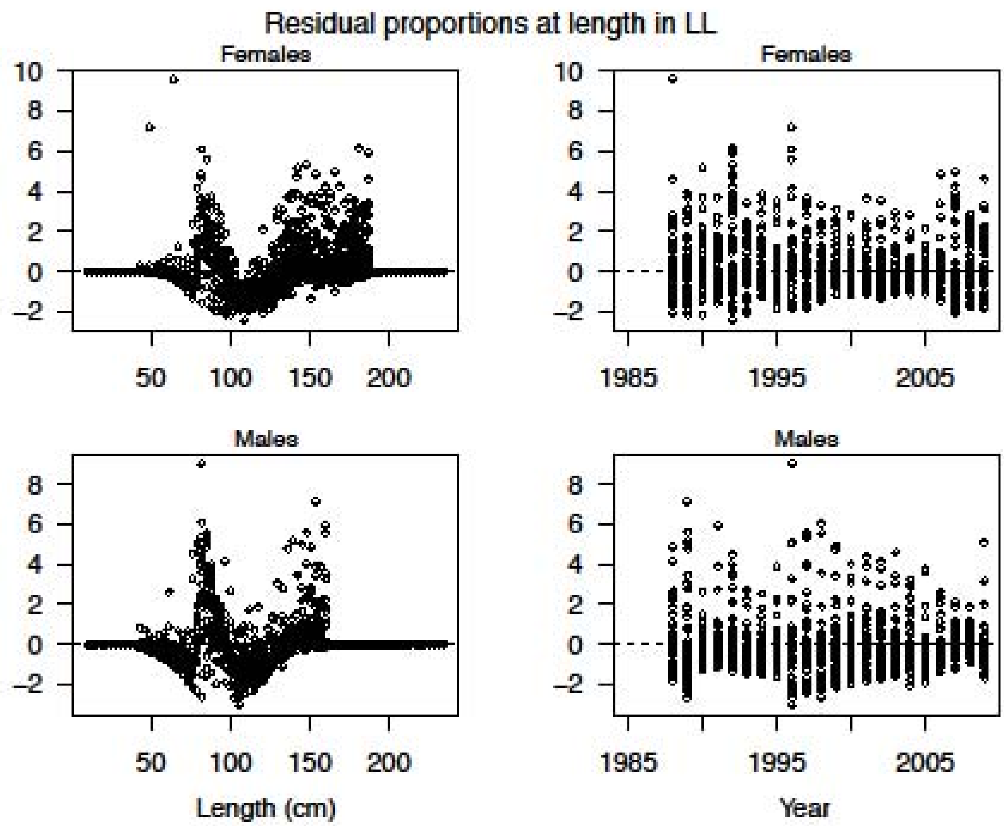

Females
Proportions at length in LL
Males
1992
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.10
0.08
0.06
0.04
0.02
0.00
50
100
150
200
1993
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1994
0.08
0.06
0.04
0.02
0.00
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1995
0.10
0.08
0.06
0.04
0.02
0.00
0.12
0.10
0.08
0.06
0.04
0.02
0.00


Females
Proportions at length in LL
Males
1996
1997
1998
1999
0.00
0.02
0.04
0.06
0.08
0.05
0.10
0.15
0.20
0.01
0.03
0.05
0.07
50
100
150
200

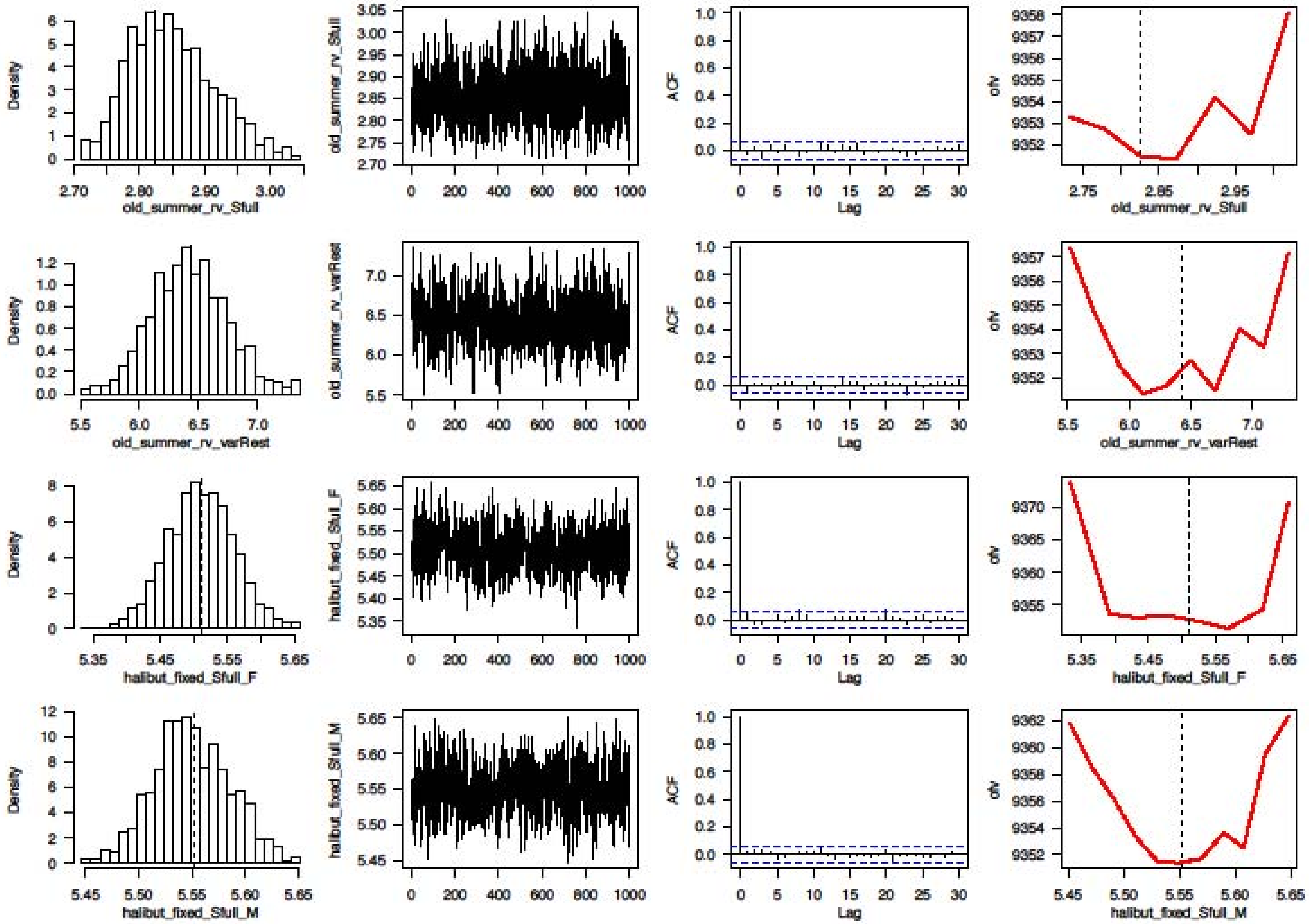

Females
Proportions at length in LL
Males
2000
2001
2002
2003
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.08
0.10
0.12
50
100
150
200

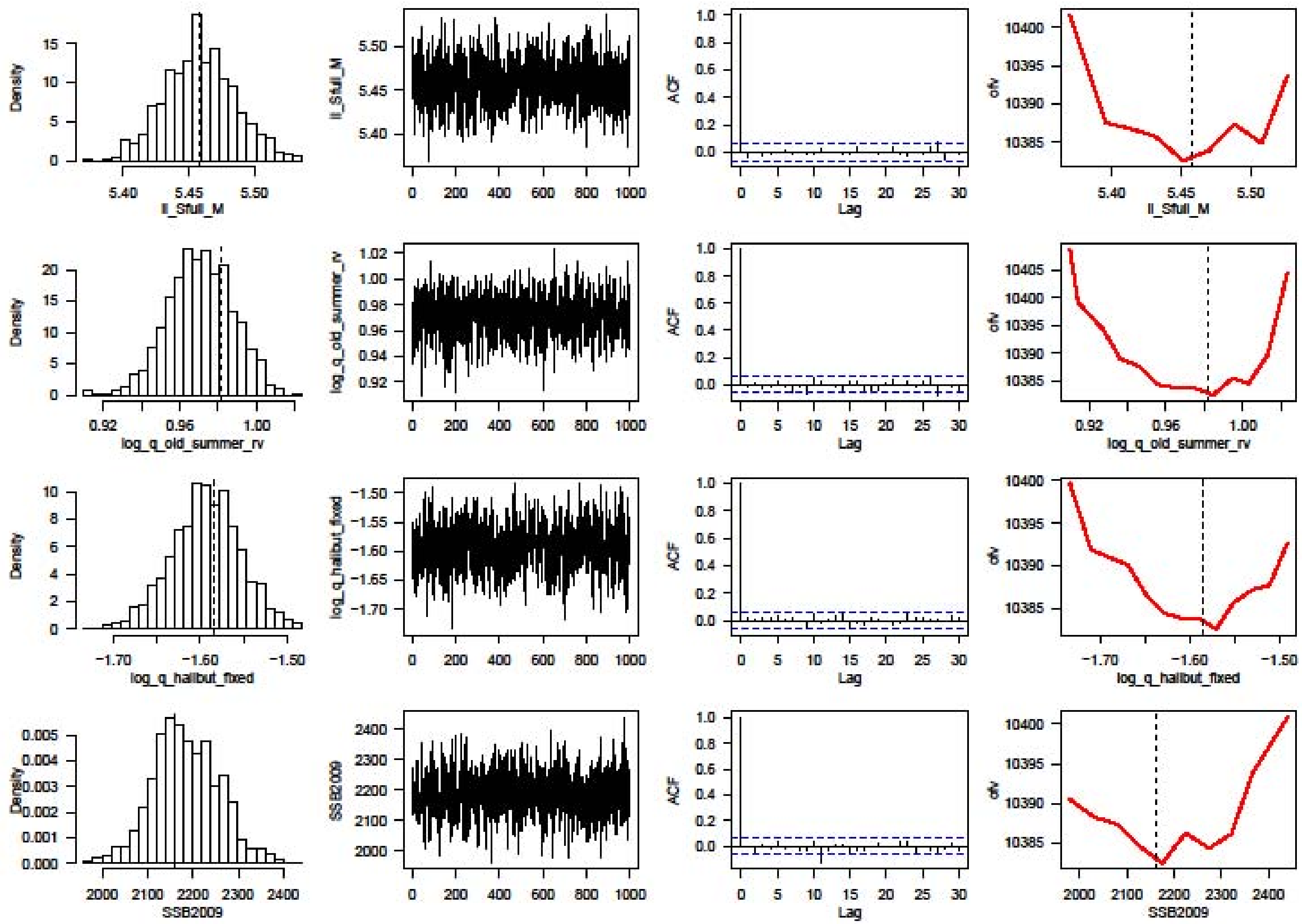

Females
Proportions at length in LL
Males
2004
2005
2006
2007

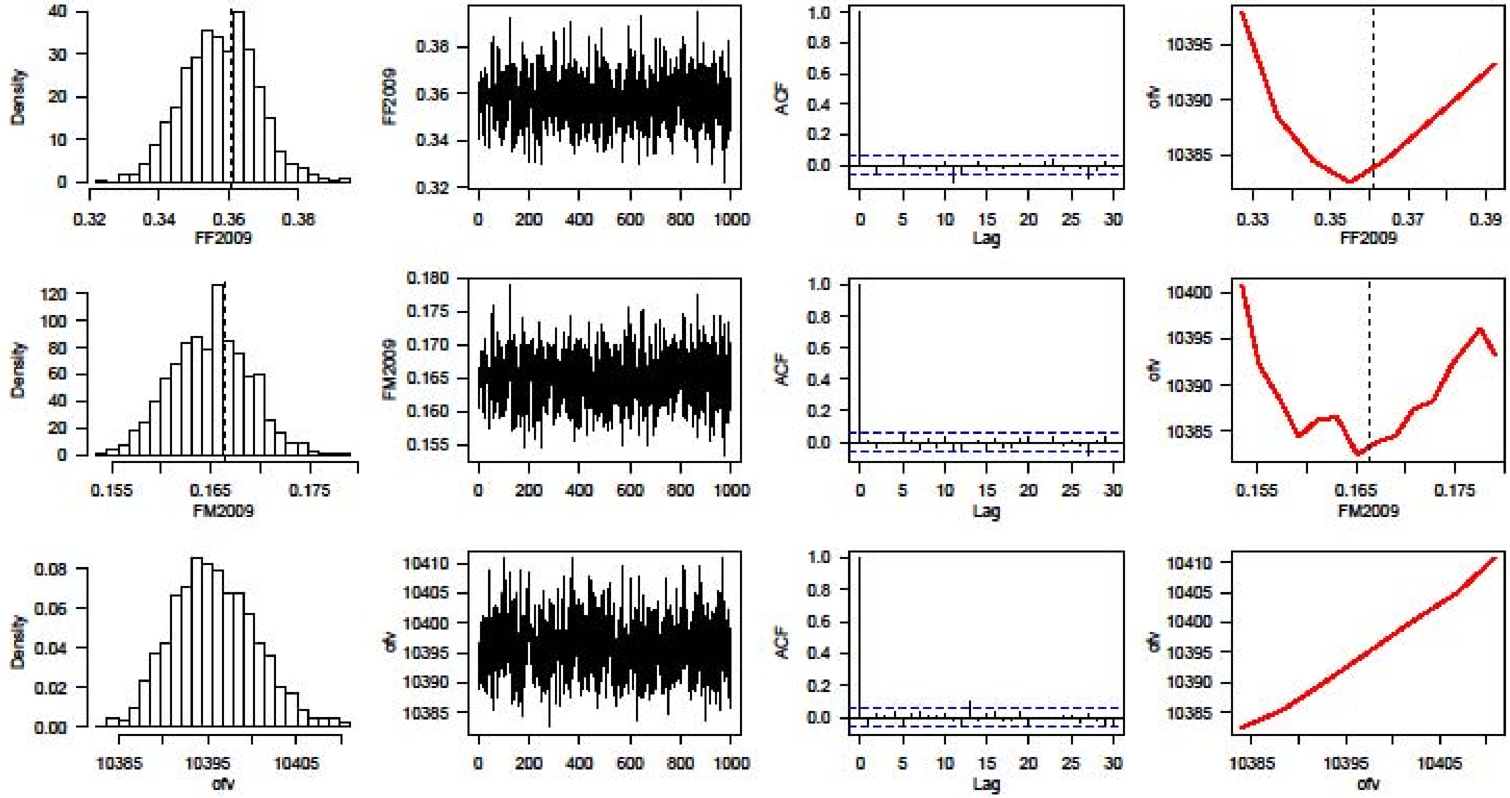

Females
Proportions at length in LL
Males
2008
2009
0.04
0.03
0.02
0.01
0.00
0.08
0.06
0.04
0.02
0.00
0.15
0.10
0.05
50
100
150
200


Residual proportions at length in LL
Females
Females
Males
Males
10
8
6
4
2
0
−2
50
100
150
200
1985
1995
2005
Length (cm)
Year

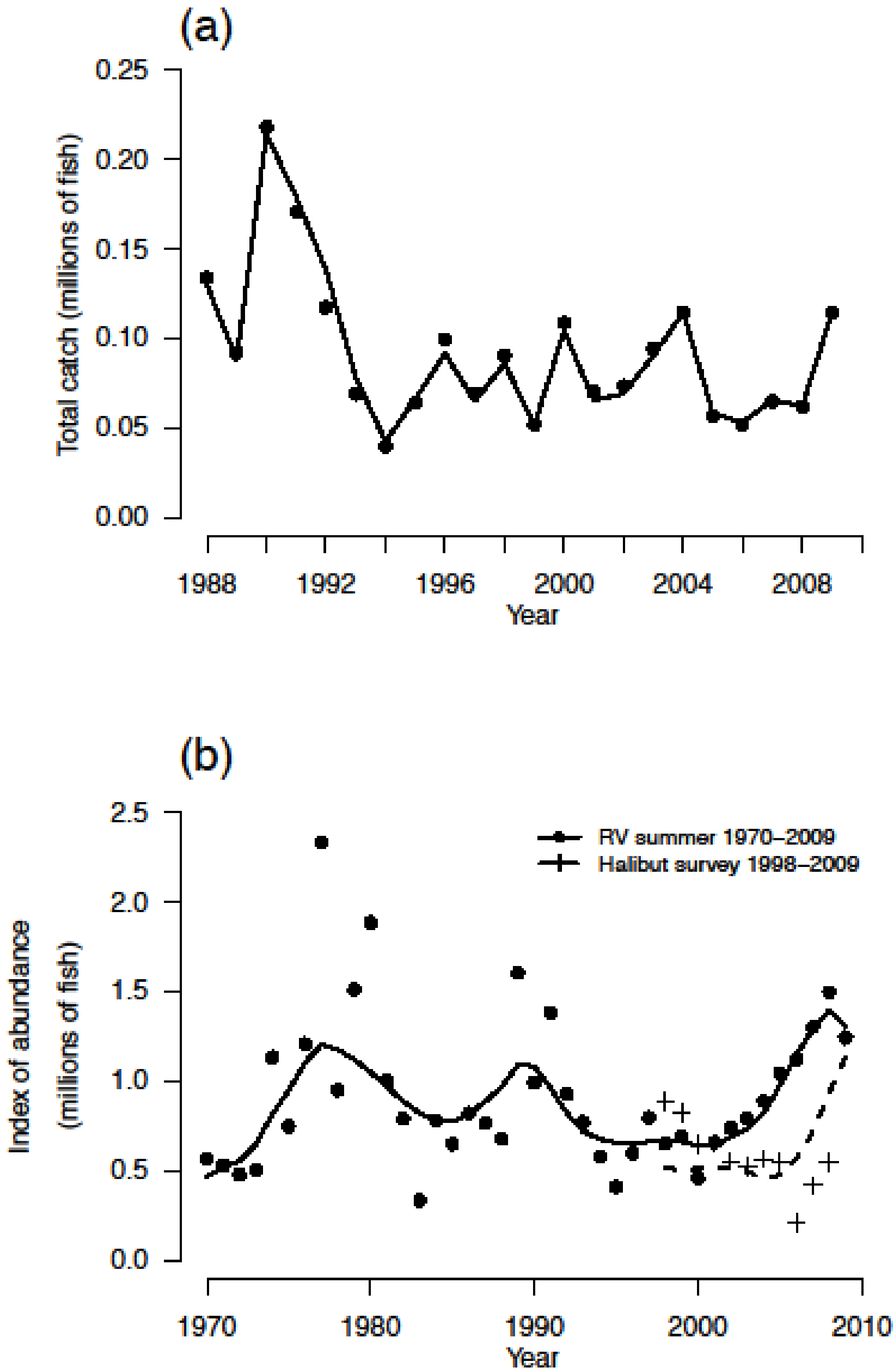
Appendix D. *Monte Carlo Markov-Chain (MCMC) simulations and Maximum Likelihood Estiamtes (MLE, vertical dashed line).*

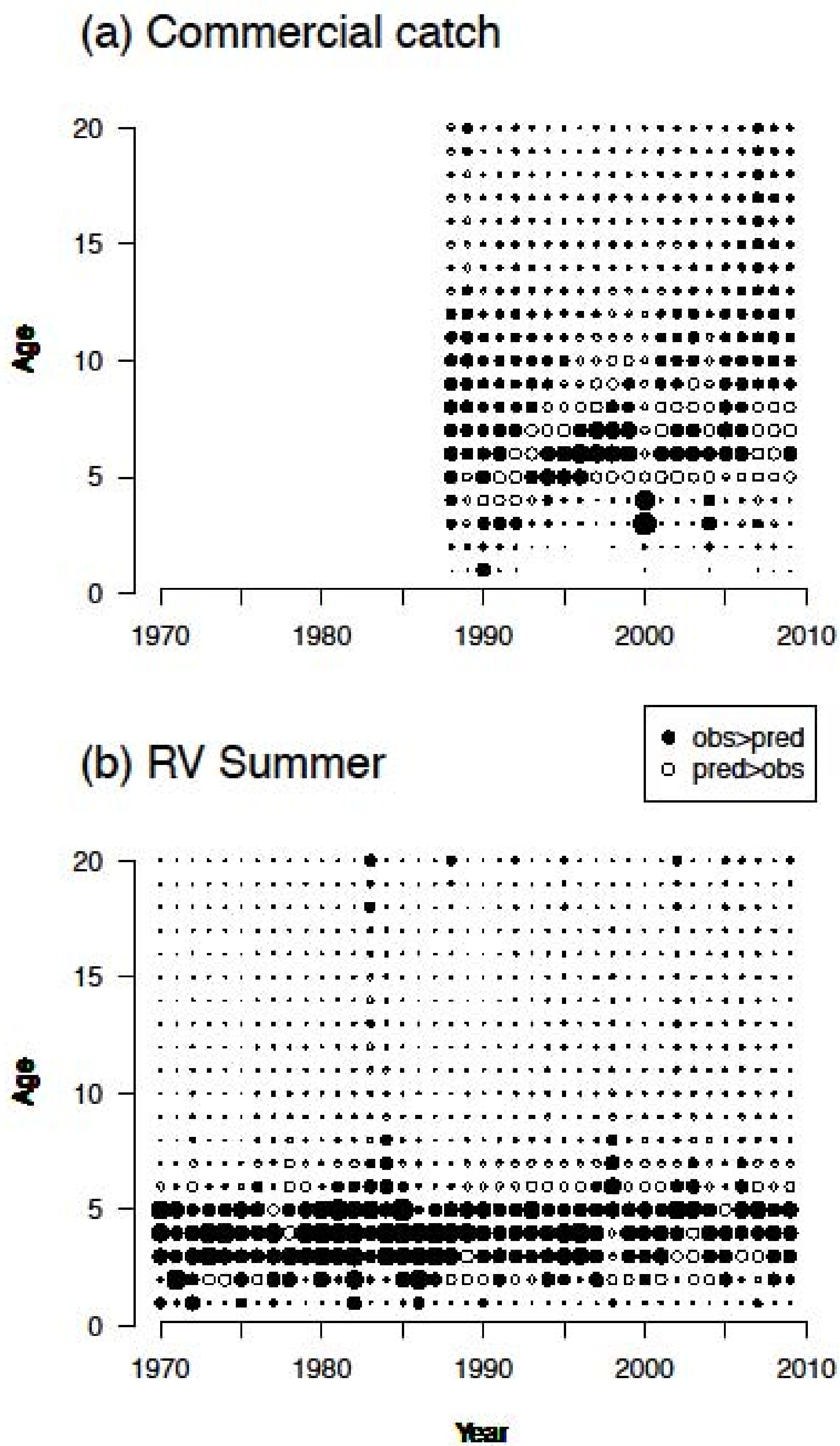


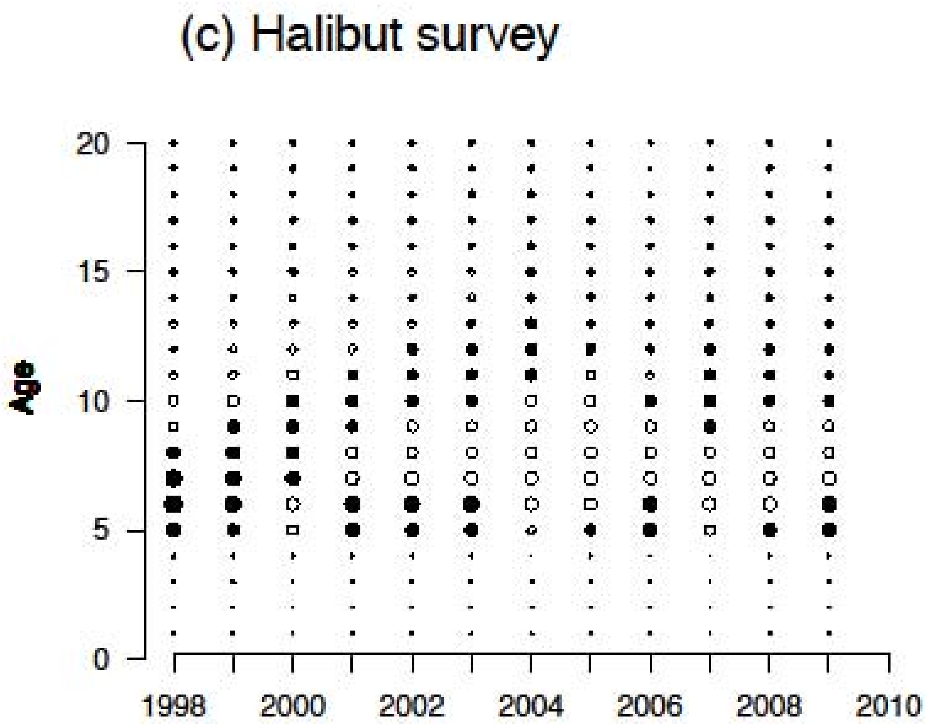

Density
ll_Sfull_M
ACF
Lag
ofv
log_q_old_summer_rv
log_q_halibut_fixed
SSB2009


Density
FF2009
FM2009
ofv
ACF
Lag

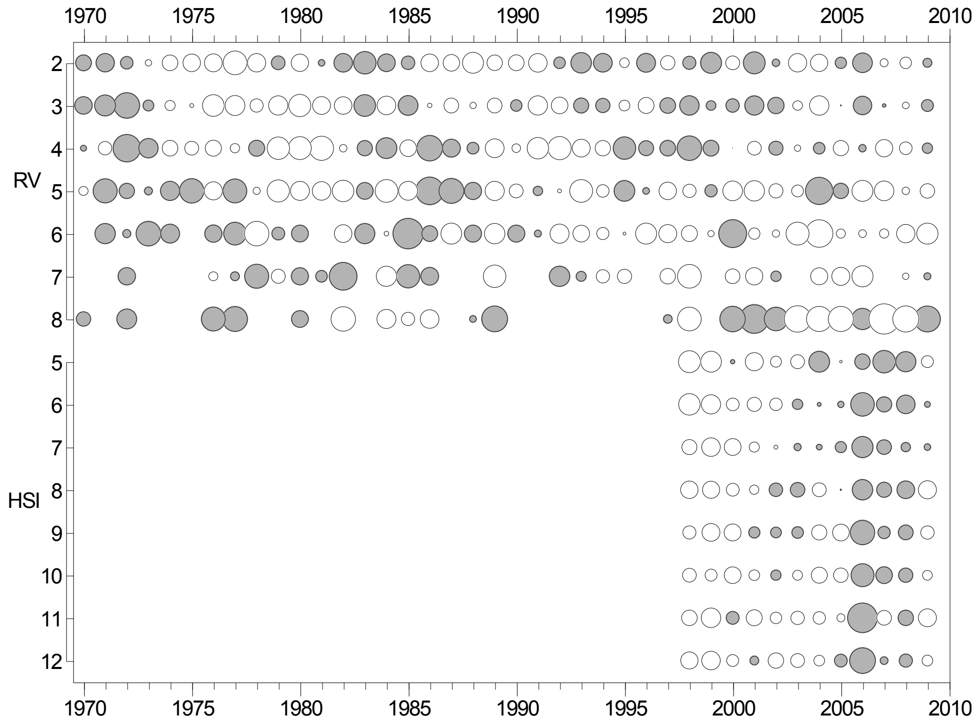
Appendix E. *Model fit and residual plots from the halibut catch at age (CAA) model.*

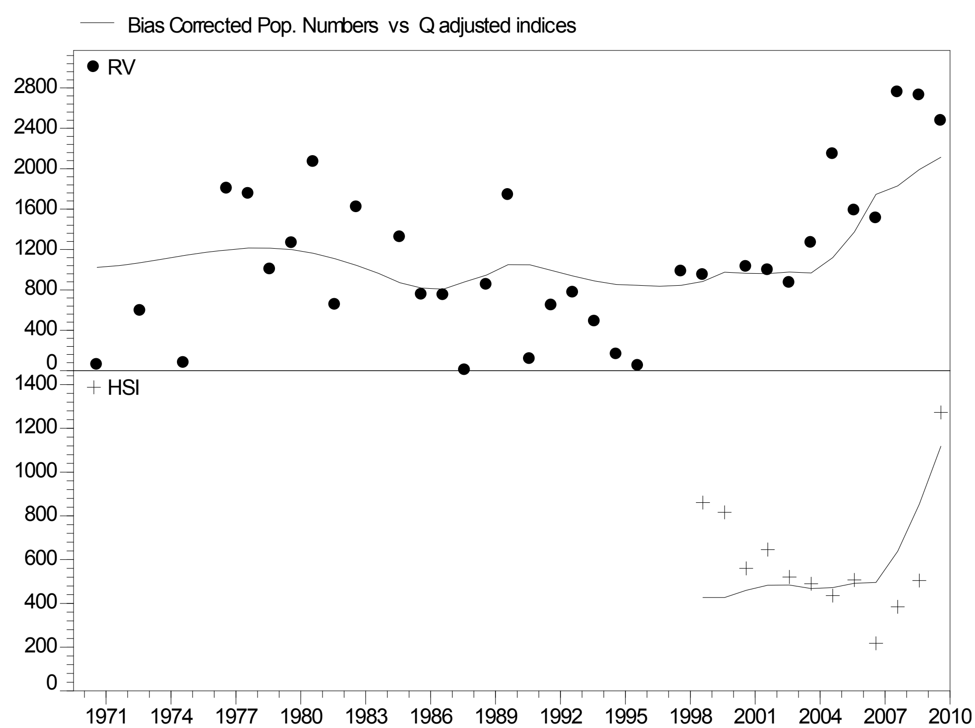



(a) Commercial catch
Age
0
5
10
15
20
1970
1980
1990
2000
2010
(b) RV Summer
obs>pred
pred>obs
Age
0
5
10
15
20
1970
1980
1990
2000
2010
Year


(c) Halibut survey
Age
20
15
10
5
0
1998
2000
2002
2004
2006
2008
2010

Appendix F. *Residual plots for the RV and halibut survey index (HSI) catch at age, fit to the RV and HSI abundance index, and projections for the virtual population analysis (VPA) model.*





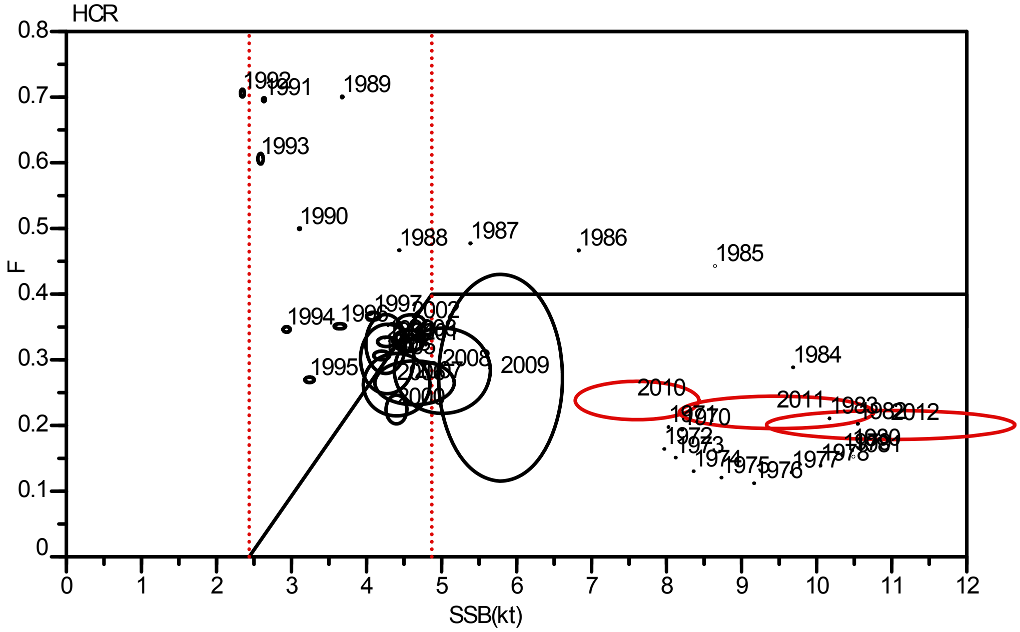


Figure F1. Harvest control rule for halibut using VPA data. The red lines mark the boundaries between critical, cautious and healthy domains. The history of the stock is shown as labelled points and uncertainty as ovals (1SD in each dimension). The stock was projected ahead for 3 years using 2000t per year.