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Assessment of Witch Flounder (*Glyptocephalus cynoglossus*) in the Gulf of St. Lawrence (NAFO Divisions 4RST), February 2017

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Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Witch Flounder (*Glyptocephalus cynoglossus*) are slow growing and late maturing. In the 1970s, the mean length of a 12-year-old female in the southern Gulf of St. Lawrence was only 41 cm, and the age at 50% maturity of females was 10 years. Because of these life-history characteristics, this species is particularly vulnerable to overexploitation. A fishery for Witch Flounder developed in the Gulf of St. Lawrence (NAFO Divisions 4RST) in the 1950s. Annual landings averaged over 3,500 t in the 1960s and 1970s, declining to an average of 1,800 t in the 1980s. Landings declined further in the early 1990s to a low of 320 t in 1995. Landings then increased to an average of 850 t annually in 1998-2008 but declined again in 2009-2010. While the total allowable catch remained at 1,000 t until 2011, landings in 2011 were 425 t. The total allowable catch was reduced to 500 t in 2012 and to 300 t in 2013 where it has remained since. Landings have closely matched the total allowable catch for the period 2013-2016. A research vessel (RV) survey index of commercial biomass (fish 30 cm or longer) was constructed for 4RST based on the August RV survey of the northern Gulf and the September RV survey of the southern Gulf. This index, available since 1987, declined sharply in the early 1990s, increased to an intermediate level in 1999 and 2000, but then declined again, fluctuating around 40% of the 1987-1990 for the period 2001-2010 and has shown an increasing trend since. A sentinel survey index of fish 30 cm or longer, based on the July sentinel survey of the northern Gulf and the August sentinel survey of the southern Gulf, is available since 2003. This index declined after 2006, was at its lowest level in 2011 and has shown an increasing trend since. A Bayesian surplus production model indicates a 90% decline in commercial biomass between 1961 and 2011 and an increasing trend since. The limit reference point (LRP) for this stock is estimated to be 10,480 t of commercial sized fish (30 cm and longer). The estimate of the biomass of fish 30 cm and longer in 2016 is 13,270 t. Based on the uncertainties in the estimates of both the 2016 biomass and the LRP, the probability that biomass is below the LRP in 2016 is 38%. Projections of the population model indicate that biomass is expected to increase, with probabilities of 74% that the biomass will be above the LRP in 2021 with annual catches of 300 t and 71% with annual catches of 500 t.

Évaluation de la plie grise (*Glyptocephalus gynoglossus*) dans le golfe du Saint-Laurent (division 4RST de l'OPANO), février 2017

RÉSUMÉ

La plie grise (*Glyptocephalus cynoglossus*) est une espèce à croissance lente qui mature à un âge avancé. Dans les années 1970, la longueur moyenne d`une femelle mature de 12 ans dans le Golfe du Saint-Laurent était de 41cm seulement, et l`âge où 50% des femelles sont matures était de 10 ans. En raison de ses traits d`histoire de vie, cette espèce est particulièrement vulnérable à la surexploitation. Une pêcherie visant la plie grise s`est développée dans le Golfe du Saint-Laurent (divisions 4RST de l`OPANO) dans les années 1950. Les débarquements annuels étaient supérieurs à 3,500 t en moyenne dans les années 1960 et 1970, et ont diminué à une moyenne de 1,800 t dans les années 1980. Les débarquements ont continué à diminuer au début des années 1990 pour atteindre un minimum de 320 t en 1995. Les débarquements ont ensuite augmenté vers une moyenne annuelle de 850 t entre 1998 et 2008 mais ont décliné de nouveau en 2009-2010. Malgré un total autorisé des captures maintenu à 1,000 t jusqu`en 2011, les débarquements en 2011 étaient de 425 t. Le total autorisé des captures fut réduit à 500 t en 2012 et à 300 t en 2013 où il demeure jusqu`à ce jour. Les débarquements ont correspondu de près au total autorisé des captures pour la période 2013-2016. Un indice de biomasse commerciale (poissons de 30 cm et plus) dans les divisions 4RST de l`OPANO a été calculé à l`aide des données des relevés par navire de recherche du mois d`août (nord du Golfe) et du mois de septembre (sud du Golfe). Cet indice, disponible depuis 1987, a fortement diminué au début des années 1990, a augmenté à un niveau intermédiaire en 1999 et 2000 pour ensuite continuer son déclin et fluctuer à environ 40% du niveau 1987-1990 durant la période 2001-2010 et exhibe depuis une tendance positive. Un indice calculé à l`aide des relevés des pêches sentinelles est disponible depuis 2003. Cet indice a diminué après 2006, était à son plus bas niveau en 2011 et montre une tendance positive depuis. Un modèle bayésien de production excédentaire indique un déclin de 90% de la biomasse commerciale entre 1961 et 2011 et une tendance positive depuis. Le point de référence limite (PRL) pour ce stock est estimé à 10,480 t de poissons de tailles commerciales (30 cm et plus). L`estimation de la biomasse de poissons de 30 cm et plus en 2016 est de 13,270 t. Selon les incertitudes dans les estimations de la biomasse en 2016 et du PRL, la probabilité que la biomasse se situe sous le PRL en 2016 est de 38%. Les projections du modèle de population indique que la biomasse devrait croître, avec une probabilité de 74% que la biomasse sera au-dessus du PRL en 2021 pour une option de prise annuelle de 300 t et de 71% pour une option de prise annuelle de 500 t.

INTRODUCTION

Witch Flounder (Glyptocephalus cynoglossus) is a righteye flounder species distributed over the northern Atlantic Ocean. In the Western Atlantic Ocean, the species occurs from Cape Hatteras to the Labrador Sea. They most commonly occur in deep holes and channels and along the shelf slope on muddy bottom. Juveniles tend to occupy deeper water than adults, especially during summer (Powles and Kohler 1970; Markle 1975). Adults undertake seasonal migrations, moving into deeper water in winter and shallower water in summer (Powles and Kohler 1970). Powles and Kohler (1970) noted that the geographic extent of these migrations may be small, as little as 5-10 miles.

In the Gulf of St. Lawrence (Figure 1), Witch Flounder form dense concentrations in deep water in winter months and become more widely dispersed throughout the Gulf in the summer (Bowering and Brodie 1984). In the early 1950s, a commercial fishery for Witch Flounder developed at the south side of St. George's Bay, Newfoundland, where boats with Danish seines fished during the summer months (Bowering and Brodie 1984). In the late 1970s, large quantities of Witch Flounder were landed by offshore otter trawlers fishing in the winter months in the Esquiman Channel southwest of St. George's Bay. This led to the first catch quota for this stock, set in 1977 at a precautionary level of 3,500 t for NAFO divisions 4RS. An assessment at this time revealed large numbers of old, slow-growing fish which were frequently landed in a "jellied" condition (Bowering 1978). In 1979, the total allowable catch (TAC) was raised to 5,000 t to reduce the numbers of these old fish and stimulate growth. The TAC was reduced back to 3,500 t in 1982, once this objective appeared to have been met (Bowering and Brodie 1980; Bowering 1981).

From 1977 to 1994, the fishery for Witch Flounder in the Gulf of St. Lawrence was regulated within NAFO divisions 4RS. Landings in 4T were not subject to catch quotas, a concern given expected increases in effort for other groundfish species following the closure of the cod fisheries in the Gulf in 1993 (R. Morin, pers. comm.). Following an analysis of the distribution of Witch Flounder in the Gulf of St. Lawrence (Morin and Hurlbut 1994), the Fisheries Resource Conservation Council (FRCC) recommended that the management unit for Witch Flounder in the Gulf be redefined to include 4T (FRCC (Fisheries Resource Conservation Council) 1994). This recommendation was implemented in 1995 and a 4RST stock unit was assumed in subsequent assessments of stock status.

The stock structure of Witch Flounder in NAFO Subarea 4 was reviewed in January 2001 (O'Boyle 2001). This review examined a proposal that the Witch Flounder moving into the Cape Breton Trough in eastern 4T each summer were more closely affiliated with Witch Flounder on the northeastern Scotian Shelf (NAFO Div. 4VW) than with those in other regions of the Gulf of St. Lawrence. The review acknowledged that the stock affiliations of Witch Flounder in eastern Div. 4T are uncertain but concluded that there was insufficient evidence to warrant a revision of the management units for Witch Flounder. Thus, this assessment of stock status is based on a 4RST management unit (Figure 2).

The last full assessments of this stock took place in 2006 (Swain and Morin 2006) and in 2012 (Swain et al. 2012b). The current document presents stock status using data up to 2016.

THE FISHERY

LANDINGS

Landings of Witch Flounder in the Gulf of St. Lawrence averaged 3,400 t from 1960 to 1975 (Figure 3, Table 1). Fisheries in 4R and 4T contributed roughly equally to these landings, with relatively minor contributions from 4S (Figure 3). Landings rose sharply in 1976 with the onset of a winter fishery by large otter trawlers exploiting winter concentrations of Witch Flounder in the Esquiman Channel. Landings dropped sharply in 1981 when these large trawlers were excluded from the northern Gulf cod fishery. Landings increased from low levels near 1,000 t in the early 1980s to levels near 2,500 t by the late 1980s. However, landings declined throughout the early 1990s to a historical low of 320 t in 1995. Landings were near this low level from 1994 to 1997, when catches remained below the allocated quotas for all gear sectors. The decline in landings was particularly strong for 4R-based Danish seiners, whose landings reached only about one quarter of their allocation during the 1994 to 1997 period. This decline in landings reflected a sharp decrease in fishing effort in 4R (see below). In this period, a high incidence of crab gear interfered with the fishery for Witch Flounder in 4R in early summer, a period when fishing effort was traditionally high (Swain and Poirier 2001). The fishery during the 1994-1997 period was dominated by landings in 4T (Figure 3). In 1996 and 1997, 4T-based vessels caught about 75-80% of their allocation. Restrictions on fishing practices may have contributed to landing shortfalls during this period. For example, delays in the opening of the fishery until June precluded traditional fisheries during spring movements of Witch Flounder when catch rates tend to be high and may have contributed to the 1997 shortfall (R. Hébert, DFO Moncton, pers. comm.). Landings increased in the 1998-2000 period (Figure 3) when quotas were caught or exceeded by the fleets directing for Witch Flounder in 4R and eastern 4T. In 2000, the TAC was set at 1,000 t. Landings remained near the TAC until 2003 when they declined to 65% of the TAC. Total landings in 2004 were 750 t, 75% of the TAC. In 2004, seine fleets directing for Witch Flounder caught their quota in 4R but only 74% of their quota in 4T. In 2004, the late opening in the spring combined with bad weather in the fall prevented the 4T fleet from catching its quota. Landings were near the TAC in 2005, with the fleets directing for Witch Flounder in 4RST catching or exceeding their quota. Landings began to decline again in 2008, falling to a record low of 229 t in 2010, less than 25% of the TAC. In 2011, landings increased in 4R to about 75% of the quota allocated to the 4R fleet, but landings by the 4T fleet remained low at about 25% of their quota allocation. The TAC was reduced to 500 t in 2012 and then to 300 t in 2013 where it remains. Since 2013, the TAC has been allocated equally to the 4R and the 4T fleets, and both fleets have since caught the near totality of the yearly TAC.

The fishery for Witch Flounder has been conducted almost entirely by mobile gears (Table 1). Danish seines have dominated the landings, except during the 1976-1980 period when winter catches by offshore trawlers contributed heavily to the landings. Since 1991, 87-100% of landings have been from unit areas 4Rd, 4Tf, 4Tg and 4Tk (Figure 4). The proportion of landings was highest from 4Rd until 1994 when landings in this unit area declined sharply (Figure 4). Landings in 4Rd remained low from 1994 to 1997, returning to their earlier levels in 1998-2008. Landings have remained fairly steady in 4Tf and 4Tg. These areas dominated the fishery in the 1994-1997 period (Figure 4). Since 1998, 4Rd and 4Tfg have contributed roughly equal portions of the landings, though 4Rd dominated the landings in 2011. Contributions from 4Tk and 4Tnoq (labelled “Other” in Figure 4) are now fairly minor.

While landings during the period 1976-1981 were primarily from the trawl fishery operating in the winter months, the fishery for Witch Flounder has steadily moved to a directed fishery prosecuted by seine between May and September (Figure 5). The fishery for Atlantic Cod ceased in 1993, explaining the disappearance of this species as the Target Species in the bottom panel of Figure 5. Similarly, the fishery for American Plaice was greatly reduced between the mid 1980s to the mid 2000s, such that almost 100% of Winter Flounder landings now come from the directed fishery. The 4R and 4T fleets now land the bulk of 4RST Witch Flounder (Figure 6).

CATCH-AT-LENGTH

The length composition of samples from the commercial fishery differed dramatically between samples collected in the 1970s and early 1980s and those collected in the 2000s (Figure 7). The proportion of fish 40 cm and longer was 76% for the period 1975-1979 and 16-22% for the period 2005-2009. For the period 2015-2016, the proportion of fish 40 cm and longer increased to 23-30%. In recent years the totality of the Witch Flounder landings have come from NAFO Divisions 4R and 4T from mobile gear (Figure 8). The length frequencies from the commercial fishery suggest that the proportion of fish 40 cm and longer has increased in recent years and there is no evidence for incoming year-classes as the length frequency distributions for the periods 2010-2016 are essentially zero for fish 30 cm and shorter.

RESEARCH SURVEY DATA

BACKGROUND

Two stratified random bottom-trawl surveys were available to provide fisheries-independent information about Witch Flounder in NAFO Divisions 4RST. One survey has been conducted in the southern Gulf of St. Lawrence each September since 1971 (Figure 9), while the second has been conducted in the Estuary and the northern Gulf of St. Lawrence since 1984 (Figure 10). However, Witch Flounder length frequency data (required for standardization between the two surveys) is available only since 1987 for the August survey.

Fishing in the September survey was by the *E.E.Prince* from 1971-1985, by the *Lady Hammond* from 1985-1991, by the *Alfred Needler* in 1992 – 2002 and 2004-2005, by the *Wilfred Templeman* in 2003, and by the *Teleost* since 2004. Comparative fishing occurred between the *E.E.Prince* and *Lady Hammond* during the 1985 survey, between the Lady Hammond and the Alfred Needler prior to the 1992 survey and between the *Alfred Needler* and *Teleost* during the 2004 and 2005 surveys. The *E.E.Prince* used a *Yankee-36* trawl and subsequent vessels used a *Western IIA* trawl. In all years, the target fishing procedure was a 30-min tow at 3.5 knots, for a standard tow of 1.75 nautical miles. Fishing was conducted in day only by the *E.E.Prince* and throughout the 24-h day by the other vessels. Further details of procedures for the southern Gulf survey are given by Hurlbut and Clay (1990).

In the August survey, fishing was by the *Lady Hammond* using a *Western IIA* trawl from 1984 to 1989, by the *Alfred Needler* using a *URI* shrimp trawl from 1990 to 2003, and by the *Teleost* using a *Campelen* trawl since 2004. Comparative fishing occurred between the *Lady Hammond* with a *Western IIA* and *Needler* with the *URI* during the 1990 survey and between the *Needler* and the *Teleost* during the 2005 survey. Target fishing procedures in the August survey were a 30-min tow at 3.5 knots in 1984-1989 (standard tow = 1.75 nautical miles), a 20-min tow at 2.5 knots in 1990-1992 (standard tow = 0.83 nautical miles), a 24-min tow at 2.5 knots in 1993 (standard tow = 1.0 nautical mile), a 24-min tow at 3.0 knots since 1994 using the *URI* trawl (standard tow = 1.2 nautical miles), and a 15-min tow at 3.0 knots using the *Campelen* trawl (standard tow = 0.75 nautical miles).

Based on analyses of the comparative fishing experiments, and additional analyses on diel variation in catchability of Witch Flounder, catches in the September and August surveys were standardized to a 1.75 nm night tow by the *Lady Hammond* using the *Western IIA* trawl for most analyses. Diel and vessel effects were independent of fish length, whereas differences in fishing efficiency were length-dependent between the *Western IIA* and *URI* trawls and between the *URI* and *Campelen* trawls. For some analyses restricted to lengths greater than 23 cm, adjustments between the *Western IIA* and *URI* trawls were independent of length because differences in fishing efficiency between these two gears varied little with length at these larger sizes. For analyses restricted to the August survey data since 1990, standardization was to the fishing efficiency of the *URI* trawl (D.P. Swain, unpublished analyses). Details on these adjustments are given in Appendix A of this document.

Survey indices were calculated using a set of strata sampled in most years; 415-439 in the September survey and 401-414, 801-824, 827-832 in the August survey. Estimated values for missed strata were obtained as described by Swain and Poirier (2001), Swain and Morin (2006) and Swain et al. (2012b).

LIFE-HISTORY INFORMATION

Growth

Witch Flounder otoliths collected during the 1974-1981 September surveys were aged (n = 301 males and 445 females). Growth was slow for both sexes, with a mean length at age 12 years of 40 cm for males and 41 cm for females. Age and length data were used to fit the von Bertalanffy growth model separately for males and females. The fitting was done using the non-linear least-square optimizer “nls” in R version 3.3.2 (R Core Team 2016) and provided adequate fits for both sexes (Figure 11; Table 2). Estimated asymptotic lengths (L_∞) were 69 cm for females and 54 cm for males. Size-at-age began to diverge between males and females at ages 12-15 years, consistent with the earlier maturation of males.

Bowering and Brodie (1984) reported growth rates for Witch Flounder collected from the northern Gulf during the same period (1975-1981). Their estimated growth rates were somewhat faster than those reported here, with their predicted lengths at age 12 years varying between 40 and 47 cm for males and 41 and 49 cm for females. However, the maximum ages in their data were considerably lower than those in the September data, 26 versus 34 in 1976 and declining to 16 versus 25 in 1980/1981, suggesting the possibility that ages may have been underestimated in their study.

Maturation

The main source of maturity data for Witch Flounder in the Gulf of St. Lawrence is the biological data collected during the September surveys. For late winter – early spring spawners such as Witch Flounder, there is concern about the reliability of maturity staging in September, mainly due to the difficulty in distinguishing between maturity stage 1 (immature) and maturity stages 7 and 8 (recovering/resting mature fish). Studies on other species (e.g., cod) have indicated that maturity staging of these species was reliable for September surveys prior to 1983, when the group conducting the survey changed (Swain 2011). Based on comparisons with samples collected in the spring, maturity staging of cod was unreliable in September surveys from 1983 to the early 1990s but appeared to be reliable in surveys conducted in the 2000s (Swain 2011, Supporting Information S3 and S4). The reliability of the witch maturity data from the September survey was examined by Swain et al. (2012b) which determined that staging was reliable in 1970-1982 but not in 1983-1999, consistent with results for cod (Swain 2011) and white hake (Swain et al. 2012a). Therefore, maturity information for the 1983-1999 period are excluded from the current analyses.

Based on the 1971-1982 data, the estimated lengths and ages at 50% maturity (L50, A50) were 37 cm and 10.4 years for females and 30.9 cm and 7.5 years for males (Figure 12). These values are similar to those reported by Bowering and Brodie (1984), based on Witch Flounder collected in January 1978-1981 in the northern Gulf; averages of 41.4 cm and 10.3 years for females and 31.5 cm and 6.9 years for males.

The data from surveys in the 2000s suggest that maturation is now earlier than in the 1970s, with L50 estimated to declined from 33 and 39.6 cm to 26.2 and 28.3 cm for males and females respectively based on the 2000-2009 data and to 26.6 and 29.2 cm based on the 2010-2016 data (Figure 13). While the reliability of the recent September data is uncertain, sampling in the Cape Breton Trough in late April and early May in 2009 to 2011 also indicates earlier maturation. Of 490 individuals sampled at lengths of 26 to 54 cm, all but one fish were mature including 30 males less than 31 cm in length and 32 females less than 35 cm in length. Earlier maturation is an expected evolutionary response to increased mortality at larger sizes, such as that imposed by fishing (Law and Grey 1989; Law 2000) or predation (Reznick and Ghalambor 2005; Swain 2011).

Geographic Distribution

Small pre-commercial sizes of Witch Flounder (<30 cm in length) tend to be restricted to the deep waters of the St. Lawrence Estuary and the Laurentian, Anticosti and Esquiman Channels (Figures 1 and 16). Densities of these small Witch Flounder tended to be high in the Estuary in all time periods with the exceptions of the 1996 to 1998 period. Densities of these small fish in both the Estuary and in the channels have been high since 2008.

Larger commercial-sized Witch Flounder (≥30 cm) tend to move up onto the shelves during the summer feeding season, with concentrations occurring in the Cape Breton Trough west of Cape Breton Island, the Chaleur Trough and Shediac Valley east of the Gaspe Peninsula and the shelf off western Newfoundland, as well as in the Estuary (Figures 15 and 17).

Since the last assessment in 2012, the density of Witch Flounder 30 cm and greater has increased in the Estuary, in western Newfoundland and around Anticosti Island (Figure 17).

Length Composition

Population length distributions for the whole stock area are available since only 1987 (Figure 18). Abundance of commercial sizes (30+ cm) declined sharply in the early 1990s. Abundance of fish 30-40 cm in length recovered in the late 1990s and early 2000s, but abundance of larger (40+ cm) fish has shown no sign of recovery. Abundance of fish under 25 cm has been generally greater since 1990 than in the 1987 to 1989 period. This may reflect ineffective adjustment for the change in trawl in the northern Gulf survey in 1990 and/or improved recruitment. Relatively high abundances in the 15-25 cm interval in the early 1990s, the late 1990s and early 2000s and in 2009 to 2012 suggest the appearance of a number of strong year-classes which may be responsible for the recovery and maintenance of abundance at the smaller commercial sizes (30-40 cm). However, survival of these strong year-classes does not appear to be sufficient to produce any recovery in biomass at larger sizes (40+ cm). Since the last assessment in 2012, the abundance of commercial sizes has steadily increased and there is evidence of another strong year-class entering the stock in the last two years.

A long-term perspective of the population length distributions is available for the portion of the stock occurring in the southern Gulf of St. Lawrence in September (Figure 19). In the 1970s and early 1980s, 47% to 88% of the Witch Flounder caught in the September survey were 40 cm or greater in length, and 2% to 21% were 50 cm or greater. In contrast, for the period 2006 to 2011, this had declined to 6% and 0.1% respectively. In contrast, 1% to 8% of the Witch

Flounder caught in the 1970s and early 1980s were less than 30 cm in length whereas 20% to 47% of those caught in 2006 to 2011 were in this size range. Since the last assessment in 2012, there has been a steady increase in the mean length of individuals (Figure 19), 12% to 16% of individuals were less than 30 cm and 6% to 13% were 40 cm or greater.

SENTINEL SURVEY DATA

BACKGROUND

Two mobile-gear sentinel surveys have been conducted in the northern Gulf of St. Lawrence beginning in 1995, one in early summer (usually mostly in July) and one in fall (late September and October). Each survey is conducted by nine otter-trawlers, each equipped with the same trawl and rockhopper gear. Since 1997, a restrictor cable has been used to standardize the horizontal opening of the trawl. The survey follows a stratified random design using the same strata as the August research vessel survey except that the sentinel surveys do not extend as far into the Estuary as does the RV survey. Additional discretionary tows conducted on observed fish concentrations were not included in this analysis. The target fishing procedure is a 30-min tow at 2.5 knots, giving a standard tow of 1.25 nautical miles. Tows in the NAFO Division 3Pn strata were omitted for these analyses. The fall survey was discontinued after 2002 and results presented here are for the July survey only.

A similar sentinel survey, using the same gear and fishing procedures (except for the restrictor cable), has been conducted in August in the southern Gulf of St. Lawrence since 2003 (Savoie 2016). This survey uses the same strata as the September RV survey.

GEOGRAPHIC DISTRIBUTION

The geographic distribution of Witch Flounder catches in the mobile-gear sentinel surveys is summarised in Figure 20 (northern Gulf) and Figure 21 (southern Gulf). There is evidence for an increase in fish 30 cm and longer along the Gaspe coast as well as in western Newfoundland while catches in the Cape Breton Trough appear fairly constant since 2007, after higher catches were observed in 2003 to 2006.

ANALYSIS

POPULATION MODELLING - SCHAEFER SURPLUS PRODUCTION MODELS

Model Structure

We implemented a Bayesian state-space Schaefer surplus production model using JAGS (Plummer 2016) and interfaced with the R package “rjags”. The “state-space” aspect of the model means that there are two coupled components, a state process and an observation model. The state process represents the unobservable stochastic processes governing the population dynamics. The observation model describes the observation errors. We used the Schaefer surplus production model as the process model:

$$B_t = \left[B_{t-1} + rB_{t-1}\left(1 - \frac{B_{t-1}}{K}\right) - C_t\right] e^{\eta_t} \qquad (1)$$

where B_t is the biomass in the late summer/early fall of year *t*, C_t is the catch for the period spanning from September in year *t-1* to August in year *t*, *r* is the intrinsic rate of population growth and *K* is the carrying capacity. The parameter *r* was fixed at a constant level over the whole time period, or allowed to vary each decade. The parameter η_t is an independent normal random variable representing process stochasticity with mean zero and variance σ^2 (i.e. $\eta_t \sim N(0,\sigma^2)$). Models incorporated as much of the catch history as possible, starting in 1961 or 1971.

The observation component related the biomass indices $I_{i,t}$ to population biomass B_t:

$$I_{i,t} = q_i B_t e^{\varepsilon_{i,t}} \quad (2)$$

where q_i is the catchability for index *i* and $\varepsilon_{i,t}$ are independent normal random variables with mean zero and variance τ_i^2 (i.e. $\varepsilon_{i,t} \sim N(0, \tau_i^2)$) representing observation errors in biomass index *i*. The model was fit to three indices of biomass of fish 30 cm and longer. To estimate the joint posterior distribution of the model parameters, 275,000 samples were generated in each of two chains, the first 200,000 samples were discarded as a "burn-in", and every 30th sample thereafter was retained to reduce autocorrelation, yielding 5,000 samples from the joint posterior distribution.

Biomass Indices

Index 1 was the trawlable biomass of Witch Flounder 30 cm and longer (30+ trawlable biomass hereafter) in the September RV survey of 4T from 1971 to 1992. This index does not cover the entire stock area but assumes that availability to the September survey (i.e. the proportion of the stock occurring within the September survey area) does not change over time. The index was used only for the 1971 to 1982 period because the proportion of the stock occurring in the September survey area changed as the stock declined in the early 1990s (Swain et al., 2012b). Index 2 was the combined August and September RV index for 4RST 30+ trawlable biomass from 1987 to 2016. Index 3 was 30+ trawlable biomass in the combined July and August sentinel surveys from 2003 to 2016.

Both Index 2 and Index 3 are combined indices and required the merging of data coming from a variety of research vessels and gear types.

Models Priors

The prior probability distributions used for the Schaefer model parameter *r* and for the catchability coefficients of the different surveys were the same as those used in the previous assessment (Swain et al. 2012b). Briefly, an informative prior for *r* was derived using methods by McAllister et al. (2001) using life history characteristics of Witch Flounder in Divs. 4RST. The prior for the catchability coefficient of the combined 4RST index was constructed based on the selectivity curve for catchability-at-length of flatfish to RV surveys estimated by Harley and Myers (2001). Other priors were uninformative and constructed as uniform probability distribution functions.

Limit Reference Point (LRP)

Following standard practice, the Limit Reference Point (LRP) used was 40% of the estimated biomass producing the maximum sustainable yield (B_{MSY}).

Results – Single Productivity Regime

We examined a first model (model M1, hereafter) corresponding to model 7 in the previous assessment (Swain et al. 2012b), which consisted in a single productivity regime and was parameterised in terms of biomass instead of proportion of carrying capacity. This parameterisation allowed the development of a prior for starting biomass, and took into account the catch data back to 1961 and the 4T index back to 1971. The 30+ cm biomass of 4RST

Witch Flounder estimated by the single productivity regime model M1 and the fit to the three biomass indices can be found in Figure 22. The process and observation errors of model M1 can be found in Figure 23. There was no strong pattern to the residuals from the three biomass indices. Process error was autocorrelated, although there was no long term trend in process error which would indicate a serious problem in model structure. The model accounted for the long term trend but had difficulty fitting the higher frequency bumps and valleys in the indices, resulting in a pattern in the process error.

Figure 24 summarises the temporal evolution of the catch and the estimated biomass of 4RST Witch Flounder, and also reports the estimates of C_{msy}, B_{msy} and B_{2016}. The model estimates suggested that the median 30+ cm biomass was slightly above the LRP in 2016. Estimates of several quantities of management interest (with 80% credible limits in parentheses) and those obtained from the 2012 assessment are summarized in the following table.

Parameter / quantity	2016 assessment	2012 assessment
r	0.1453 (0.0974-0.1995)	0.1440 (0.0935-0.1984)
K	52.4 kt (32.9-153.2)	52.6 kt (30.9-166.1)
B_{msy}	26.2 kt (16.6-76.6)	26.3 kt (15.5-83.0)
LRP	10.5 kt (6.6-30.6)	10.5 kt (6.2-33.2)
B_t	13.3 kt (8.8-19.3); t = 2016	5.0 kt (3.3-7.4); t = 2011
C_{msy}	2.0 kt (1.2-4.7)	1.9 kt (1.1-5.0)
F_{msy}	0.072 (0.049-0.099)	0.072 (0.047-0.099)
B_t/LRP	1.20 (0.41-2.28); t = 2016	0.46 (0.14-0.91); t = 2011
$P(B_t < LRP)$	38%; t = 2016	93%; t = 2011
$P(B_t > LRP)$	62%; t = 2016	7%; t = 2011

Priors and posteriors of the model parameters and some estimated variables are shown in Figures 26 to 28. The strongly informative prior on q_2 was updated slightly by the data with the posterior shifted slightly to higher values (Figure 27), while the prior and posterior distributions for *r* were almost identical (Figure 26).

To examine model robustness, we removed the biomass index data for the four most recent years (while retaining the landings data) and projected the model forward over the years of missing data, comparing the revised predictions of population biomass to those obtained using all the available data. The revised model predictions with the missing data compared well with those obtained using all the available data (Figure 29). As expected, the uncertainty around the predicted biomass trajectory increased greatly for the years without index data.

Five-year projections were made at three levels of catch corresponding to 0 t (no fishery), 300 t and 500 t (Figures 30 and 32). Median estimates of 30+ biomass increased over the five year period at all catch levels of 0 t to 500 t. The probability that the 30+ biomass will exceed the LRP by 2021 is 77% under a catch level of 0 t, 74% under a catch level of 300 t and 71% under a catch level of 500 t (Table 3; Figure 31). Under the different catch scenarios, the percentage of the surplus production removed by harvesting ranges from 19% to 21% for a catch of 300 t and from 33% to 35% for a catch of 500 (Table 3).

Results – Changing Productivity Regimes

The second model evaluated (model2, M2 hereafter) addressed the possibility of changes in the productivity regime experienced by the stock and was implemented by allowing *r* to vary at a decadal scale. The model was the same as model M1 except that *r* was allowed to differ between the following four periods: 1961-1979, 1980-1989, 1990-1999, and 2000-2016. The prior for *r* in the first period was the same as the prior used in model M1. The prior for *r* in the other three periods was uniform between -0.2 and 0.5.

Estimates of *r* for the 1990s were somewhat lower than those for the other periods (Figure 33). Posterior medians for *r* declined from 0.182 and 0.266 in the 1961-1979 and 1980-1989 periods to 0.075 and 0.159 in 1990-1999 and 2000-2016, respectively. However, the posterior distributions for *r* overlapped broadly between all four periods, and the evidence for a decline in productivity is thus weak.

STOCK STATUS INDICATORS

The NAFO 4RST Witch Flounder is currently assessed and managed on a five-year cycle. Indicators are needed to characterise stock status in years between assessments. The indicators suggested are the biomass indices from the RV surveys conducted in the northern and southern Gulf of St. Lawrence. These indices can have significant observation error and changes in stock biomass should not be inferred from annual estimates. Moving averages are therefore suggested, with a three-year moving average recommended for tracking Witch Flounder stock biomass. Important changes in the indicator, e.g., a large change in the moving average from its value in the last assessment year, would trigger a re-assessment before the five-year period has elapsed. Currently, the TAC for this stock is set to 300 t.

In order to implement this approach it is necessary to relate the LRP from its population scale in September to the scale of the RV indices in August and September. This is done by scaling the biomass over the whole stock area to the scale of the combined 4RST index using the catchability coefficient of the index. The median value of the index’s catchability coefficient is 0.5124 and the LRP is 10,483 t, resulting in a scaled LRP of 5.3716 kg/tow (Figure 22).

The three-year moving average will be computed annually for the next five years and an assessment will be triggered if its value falls below the scaled LRP.

CONCLUSIONS

Witch Flounder is an unproductive species. Growth is very slow and maturation is at a late age. In the 1974 to 1981 period, the mean length at an age of 12 years is estimated to have been only 40 cm for males and 41 cm for females. For this same period, estimated ages at 50% maturity were 7.5 yr for males and 10.4 yr for females. Species with such low productivity are particularly vulnerable to overexploitation. An apparent shift towards earlier maturation in the NAFO Div. 4RST stock in the 2000s suggests that this stock has experienced unusually high adult mortality in recent decades

Commercial (30+ cm) biomass of 4RST Witch Flounder declined sharply in the early 1990s. There appeared to be some recovery in biomass following a reduction in landings to levels of 300 to 500 t. However, this partial recovery ceased and has been eroded following an increase in landings to the 700 t to 900 t level. Thus, the stock appears to no longer be able to support landings of only 700 t to 900 t even though annual landings averaged over 3,500 t in the 1960s and 1970s.

There has been a clear contraction in the size composition of the stock since the 1970s and early 1980s. Fish 40 cm or longer made up 70% to 80% of the landings and 86% of the September RV catch in the late 1970s but only 20% of the landings and 8% of the September RV catch during 2006 to 2011. The proportion of these large fish has increased in recent years, accounting for up to 23% of the landings and 13% of the September RV catch.

The strong year-classes that appeared in the RV survey length frequency distribution in the 1990s and 2000s and that were allowed to reach commercial size through the imposition of a TAC of 300 t in 2012 are now promoting the rebuilding of the stock. Indices of 30+ biomass show increasing trends and the population model estimates suggest that the stock is rebuilding. B_{msy} for this stock is estimated to be 26,210 t. At this biomass level, the maximum sustainable yield is estimated to be about 1,960 t, corresponding to an exploitation rate of 7%.

The limit reference point (LRP) for this stock (40% of B_{msy}) is estimated to be 10,480 t. The median estimate of the current stock level is slightly above the LRP at 13,270 t and the probability that the estimated 30+ biomass in 2016 is above the LRP is 62%.

The stock remains in the cautious zone and the probability that it will exceed the LRP by 2021 is predicted to be 77% with no fishing, 74% for an annual catch of 300 t, and 71% for an annual catch of 500 t.

Based on a model allowing decadal variation in the intrinsic rate of increase (*r*), median estimates of *r* since 1990 are less than half the values estimated for periods between 1961 and 1989, suggesting a decline in productivity. However, the evidence for a decline in productivity is weak, with the posterior distributions for *r* overlapping broadly between all periods.

ACKNOWLEDGEMENTS

The authors acknowledge Tobie Surette and Pablo Vergara for continued support in the development of analytical tools facilitating the analysis of survey data from the Gulf Region, and to Hugo Bourdages and Denis Bernier for their invaluable help in accessing and analysing sentinel and survey data from the Québec Region. We thank the crew and officers of the Coast Guard vessels responsible for the northern and southern Gulf of St. Lawrence annual research vessel surveys and the DFO staff who participated in them.

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TABLES

Table 1. Annual landings (t) of Witch Flounder in NAFO Divisions 4RST by gear type. OTB=otter trawl, OTB1=side otter trawl, OTB2=stern otter trawl, SNU=seine, GNS=gillnet, LLS=longline. Total allowable catch (TAC) is also shown.

YEAR	OTB	OTB1	OTB2	SNU	GNS	LLS	OTHER	TOTAL	TAC
1960	1912	0	0	1309	0	72	45	3338	na
1961	1428	0	0	1907	7	19	135	3496	na
1962	1342	0	0	2012	0	28	5	3387	na
1963	1561	0	0	2612	37	25	15	4250	na
1964	1377	0	0	1657	0	86	230	3350	na
1965	1137	0	0	2389	1	67	14	3608	na
1966	0	1620	39	1845	93	5	110	3712	na
1967	1	964	33	1647	36	23	10	2714	na
1968	0	1227	102	1995	46	13	7	3390	na
1969	3	1286	294	3179	0	1	0	4763	na
1970	12	1203	504	3078	8	0	0	4805	na
1971	17	1108	183	2352	11	137	13	3821	na
1972	30	968	329	636	2	7	29	2001	na
1973	68	613	56	1330	39	12	106	2224	na
1974	0	707	946	1569	15	0	10	3247	na
1975	82	771	371	1449	25	4	20	2722	na
1976	111	1606	4303	730	9	0	116	6875	na
1977	102	962	1248	715	4	0	8	3039	3500
1978	3	616	2767	938	69	3	114	4510	3500
1979	62	1065	1970	1309	120	14	21	4561	5000
1980	106	548	1618	1100	98	30	27	3527	5000
1981	108	446	267	1032	24	33	2	1912	5000
1982	93	105	122	934	24	4	0	1282	3500
1983	137	116	52	829	27	10	6	1177	3500
1984	75	110	314	536	51	19	2	1107	3500
1985	27	89	161	1127	28	7	221	1660	3500
1986	49	63	79	1216	6	2	408	1823	3500
1987	58	157	212	1671	7	0	504	2609	3500
1988	56	177	177	1835	34	1	250	2530	3500
1989	45	199	358	1698	47	0	0	2347	3500
1990	12	120	236	873	16	8	7	1272	3500
1991	8	5	173	766	36	1	4	993	3500
1992	11	3	129	825	16	2	3	989	3500
1993	1	0	95	690	17	0	94	897	3500
1994	0	0	27	387	5	0	26	445	1000
1995	0	0	20	302	6	0	0	328	1000
1996	0	1	12	479	0	0	1	493	1000
1997	0	0	73	494	3	0	0	570	1000
1998	0	0	48	816	1	0	0	865	800
1999	0	0	14	713	3	0	0	730	800
2000	0	0	81	914	1	0	0	996	1000
2001	0	0	111	705	0	0	0	816	1000

YEAR	OTB	OTB1	OTB2	SNU	GNS	LLS	OTHER	TOTAL	TAC
2002	0	0	176	847	1	0	0	1024	1000
2003	0	0	36	622	0	0	0	658	1000
2004	0	0	63	671	0	0	0	734	1000
2005	0	3	100	832	0	0	0	935	1000
2006	0	0	87	856	0	0	0	943	1000
2007	0	0	72	834	1	7	0	914	1000
2008	0	3	56	676	1	0	0	736	1000
2009	0	0	28	440	0	0	0	468	1000
2010	0	0	11	217	0	0	0	228	1000
2011	0	0	2	423	0	0	0	425	1000
2012	0	0	2	322	0	0	0	324	500
2013	0	0	5	274	0	0	0	279	300
2014	0	0	4	291	1	0	0	296	300
2015	0	0	1	248	1	0	0	250	300
MEAN	179	301	324	1110	17	11	46	1989	na

Table 2. Estimated von Bertalanffy growth parameters for Witch Flounder from the southern Gulf of St. Lawrence, 1974 to 1981.

Parameter	Females		Males	
	Estimate	SD	Estimate	SD
L_∞	69.220	3.860	53.949	2.561
k	0.053393	0.00819	0.09525	0.01965
t_0	-4.38875	1.07534	-2.26928	1.48619

Table 3. Annual probabilities that the estimated biomass of Witch Flounder >= 30 cm after fishing will be less than or equal to the Limit Reference Point (LRP) and greater than or equal to the Upper Stock Reference Point (USR) for four levels of annual catch in 2017 to 2021. Also shown are the percentages (median; 80% credibility interval) of the projected surplus production of biomass which would be extracted annually for each annual catch option.

		Catch option			
Reference	Year	0 t	100 t	300 t	500 t
B_{year} <= LRP	2017	34%	35%	36%	37%
	2018	31%	32%	33%	35%
	2019	28%	28%	30%	33%
	2020	25%	26%	28%	30%
	2021	23%	24%	26%	29%
B_{year} >= USR	2017	23%	23%	22%	21%
	2018	29%	28%	27%	25%
	2019	35%	34%	32%	30%
	2020	41%	39%	36%	33%
	2021	46%	44%	41%	37%
Percentage of surplus production removed	2017	0%	7.0% (4.6 - 11.3)	21.1% (13.7 - 34.2)	35.4% (23.0 - 57.7)
	2018	0%	6.8% (4.2 - 11.6)	20.6% (12.7 - 35.3)	34.8% (21.5 - 60.2)
	2019	0%	6.5% (3.7 - 11.6)	19.9% (11.5 - 35.9)	33.8% (19.7 - 61.8)
	2020	0%	6.3% (3.3 - 11.8)	19.5% (10.4 – 36.5)	33.2% (18.1 - 63.4)
	2021	0%	6.1% (3.0 - 12.0)	19.0% (9.5 - 37.4)	32.7% (16.7 -65.1)

FIGURES

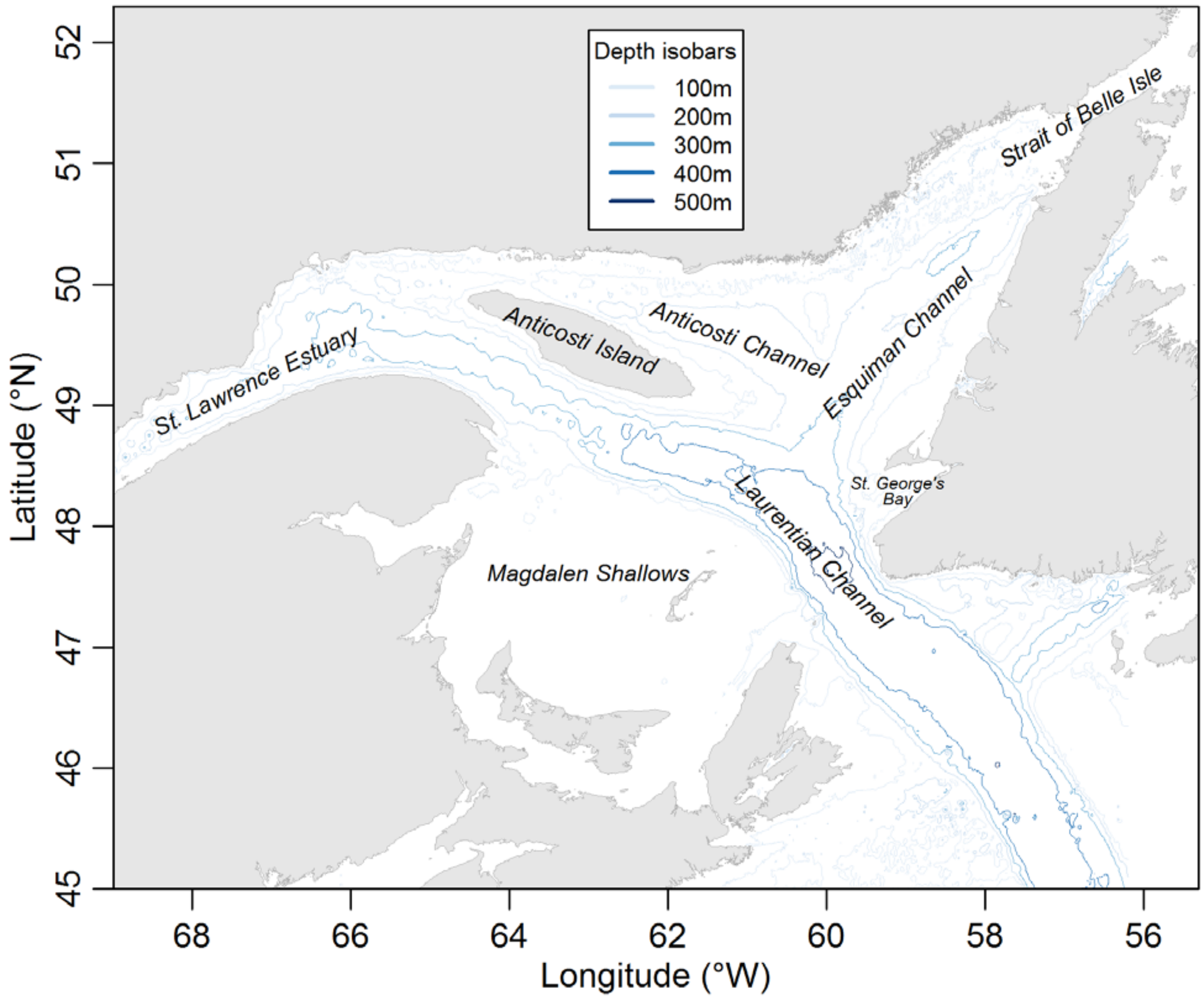

Figure 1. Map of the Gulf of St. Lawrence region showing the topographic features mentioned in the document text. Isobaths are drawn for depths down to 500 m by 100 m increments.

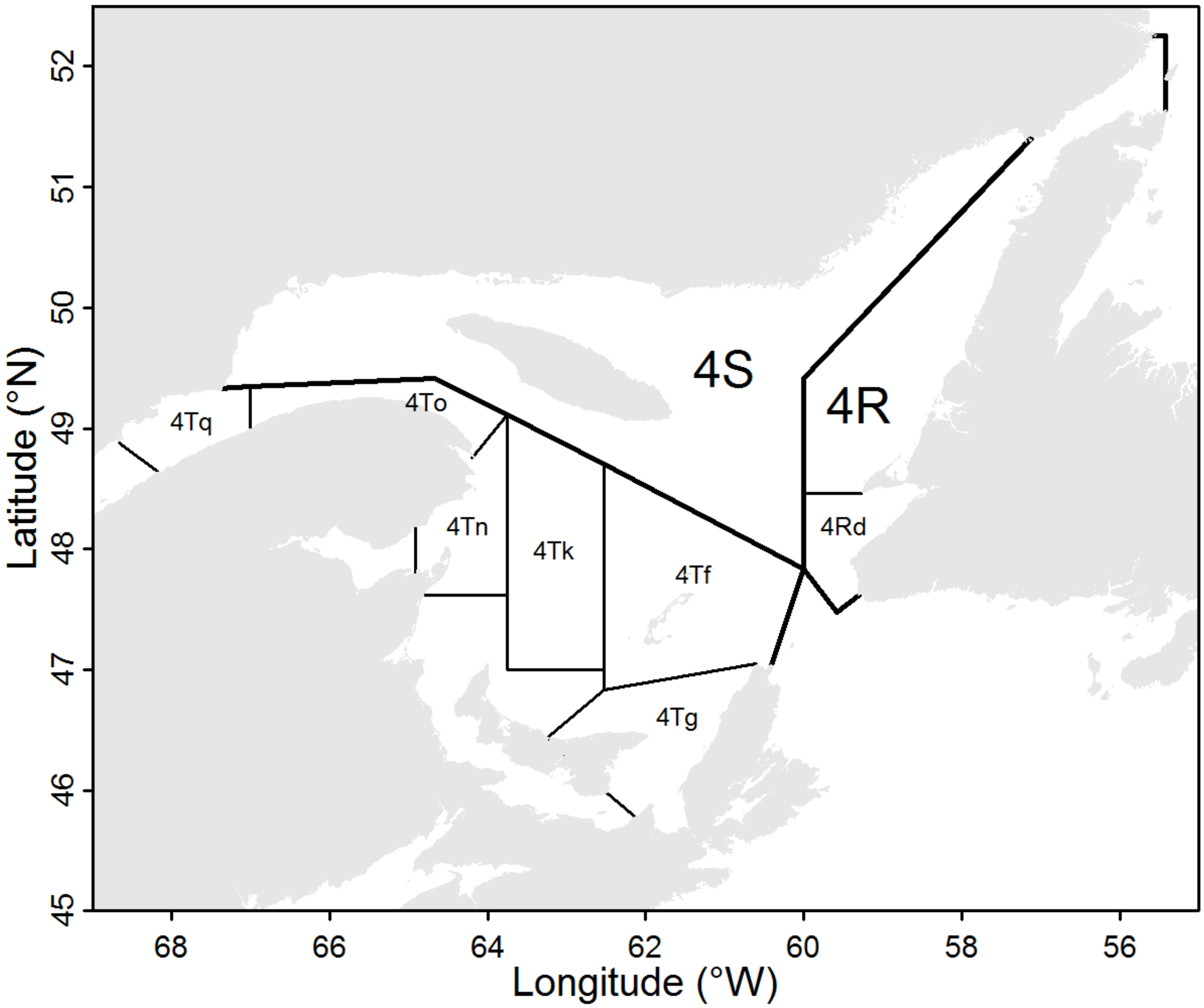

Figure 2. NAFO divisions in the Gulf of St. Lawrence. NAFO Divisions 4R, 4S and 4T are bordered by heavy solid lines. The NAFO unit areas where most Witch Flounder are caught in commercial fisheries are labelled in lower case.

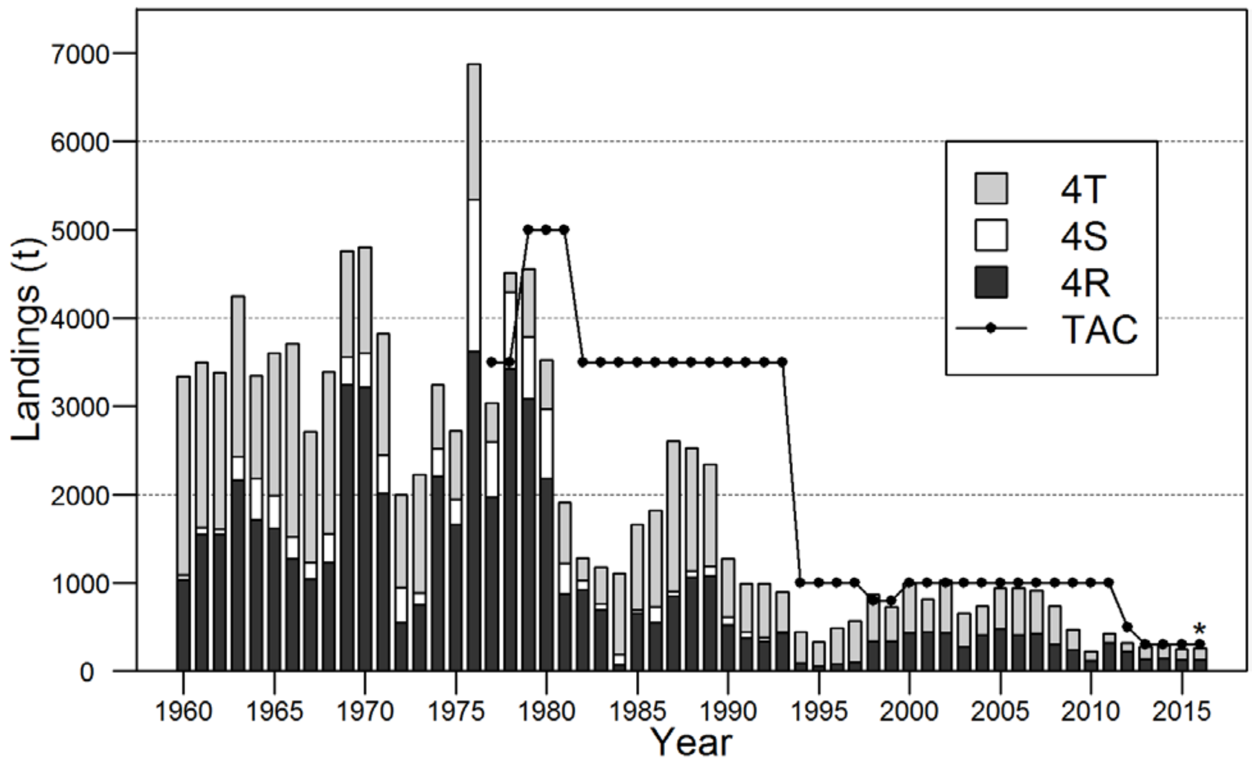

Figure 3. Landings and TAC of Witch Flounder in NAFO divisions 4RST, 1960 to 2016. The asterisk over 2016 indicates that the landings for that year are preliminary.

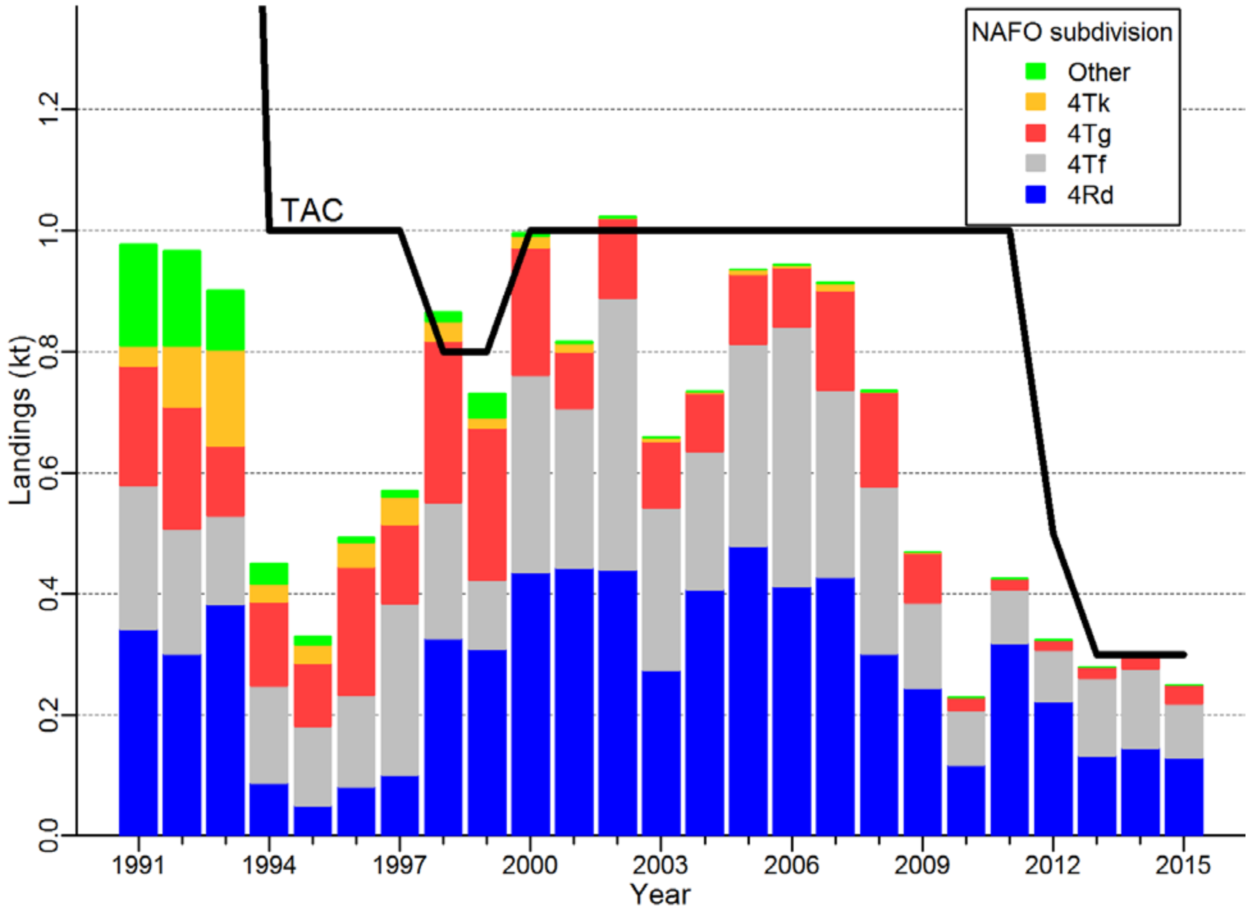

Figure 4. Landings of Witch Flounder in NAFO Div. 4RST by NAFO unit area, 1991 to 2015.

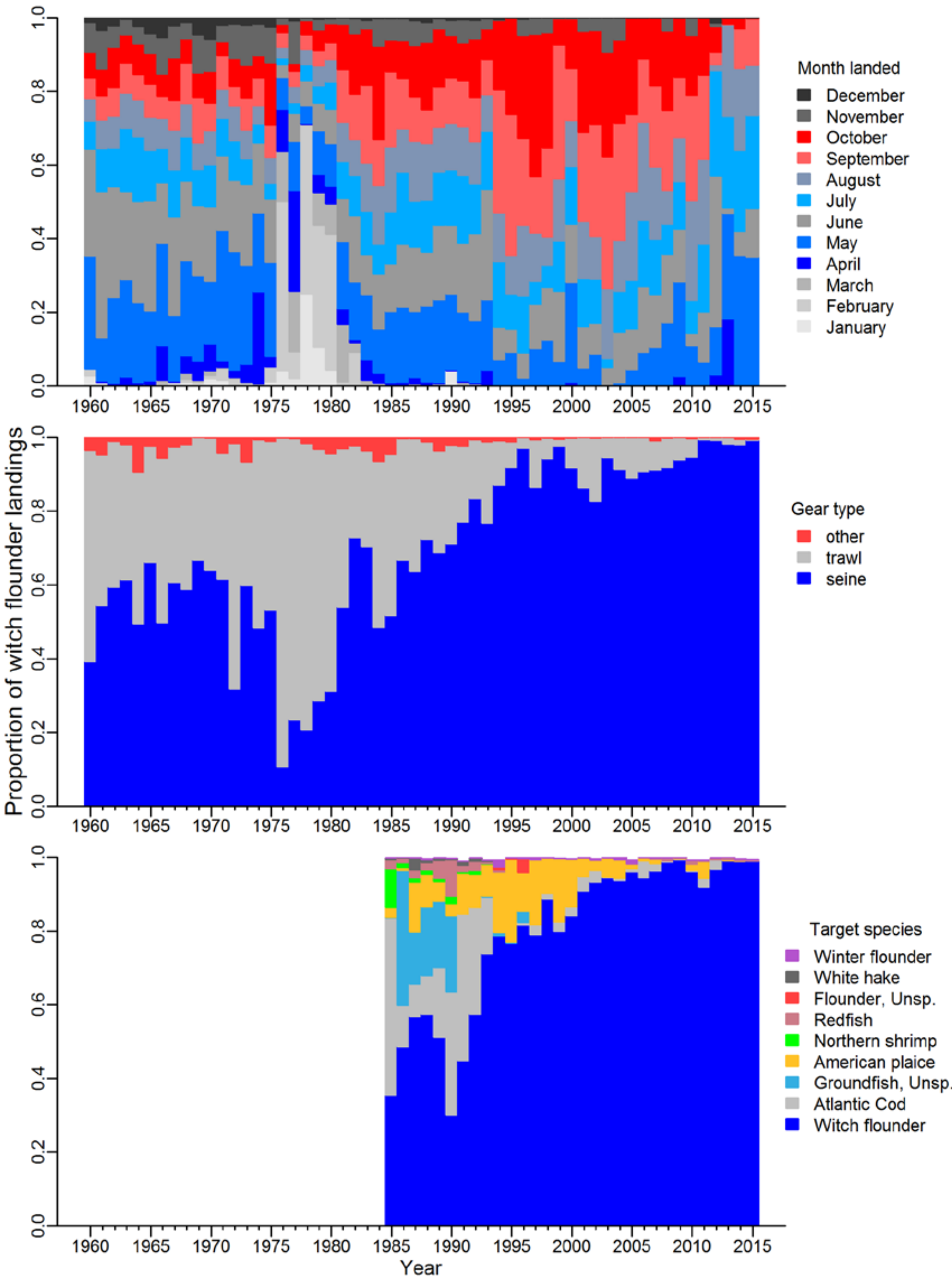

Figure 5. Proportion of annual Witch Flounder landings in NAFO Divisions 4RST by month (top panel), by type of fishing gear (middle panel) and by target fishing species (lower panel), 1985 to 2015. Data prior to 1985 come from the Northwest Atlantic Fisheries Organization (NAFO) catch statistics and did not include information about target species.

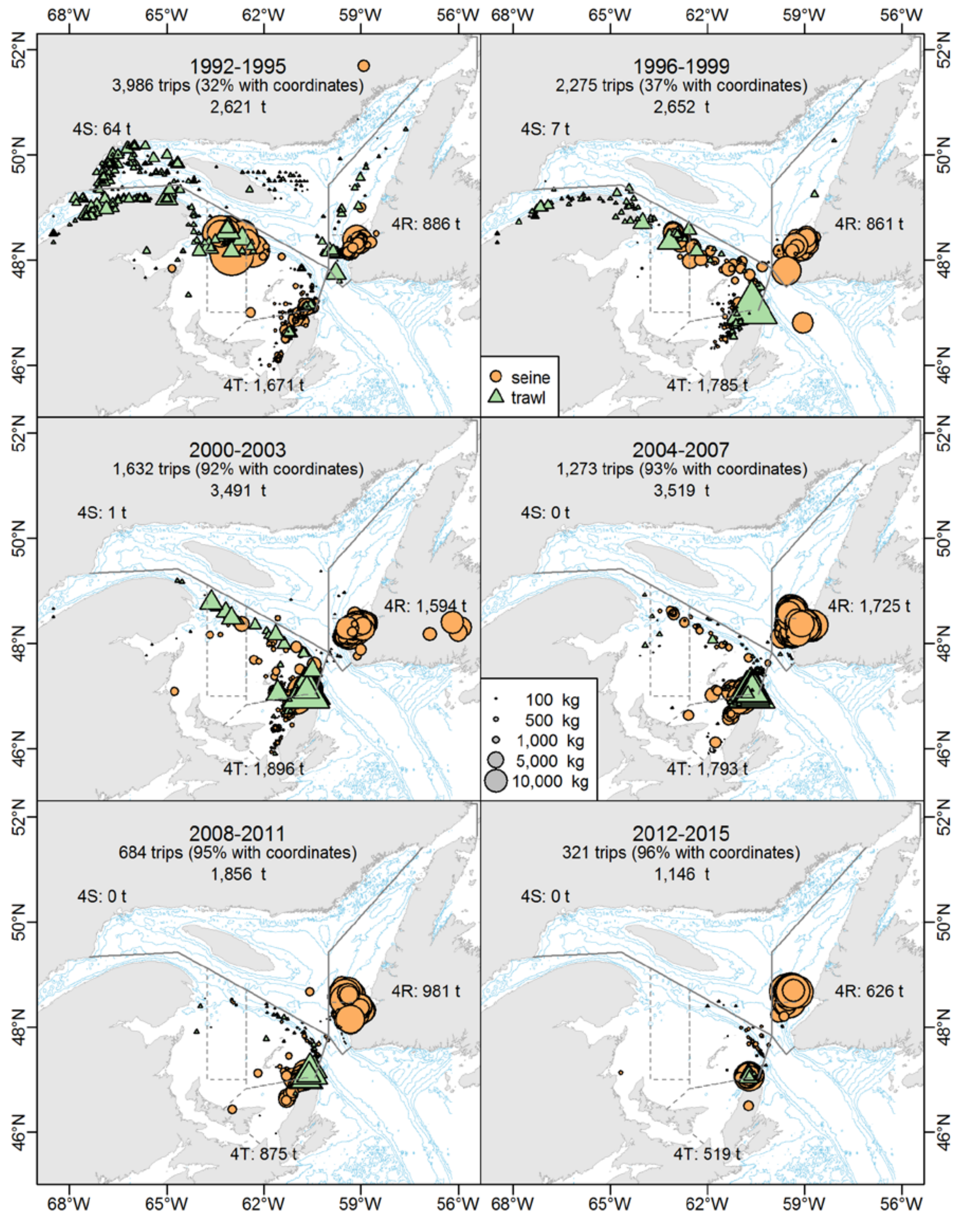

Figure 6. Geographic location of catches of Witch Flounder by gear type in NAFO Divisions 4RST, 1992 to 2015.

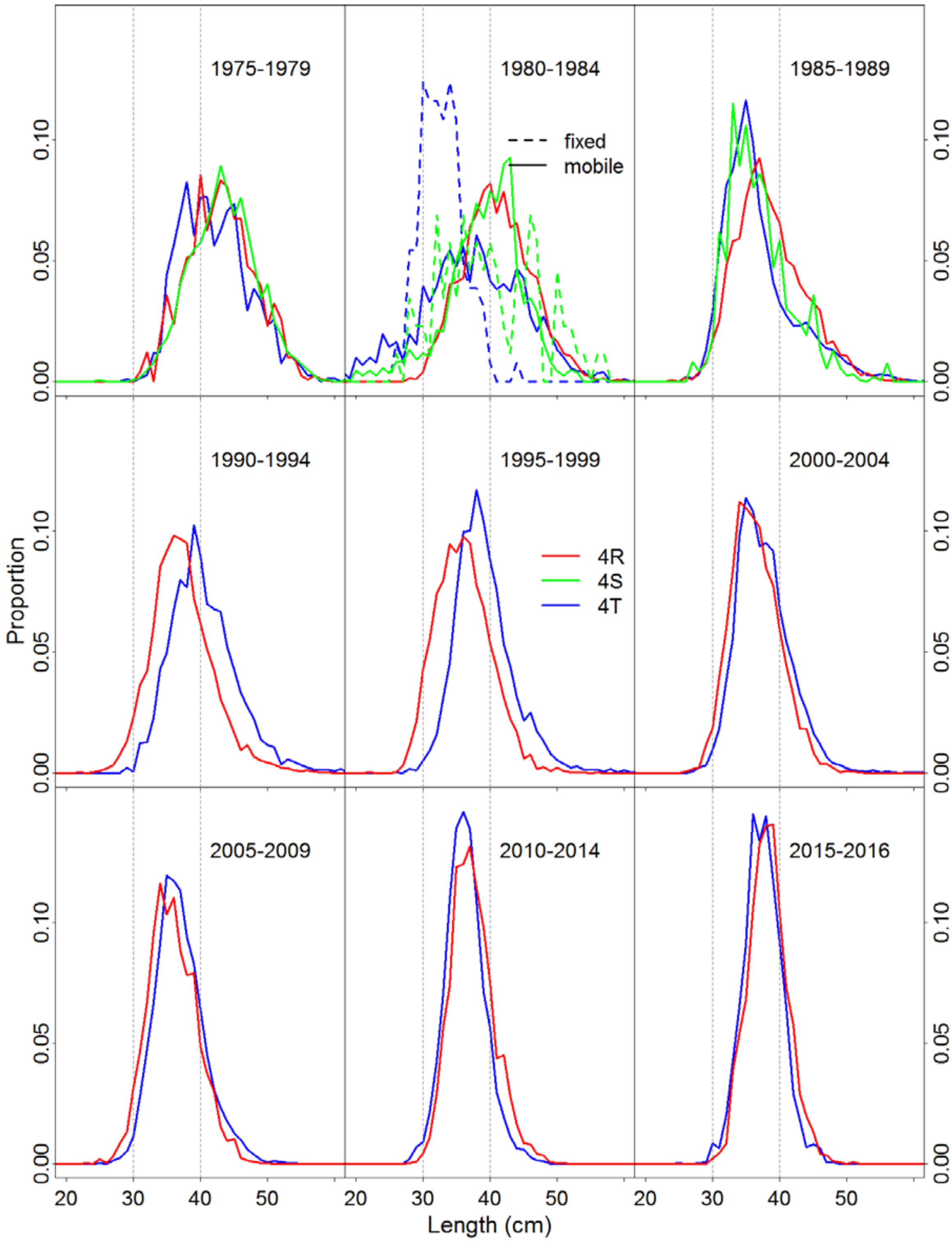

Figure 7. Average length frequencies (proportion) of Witch Flounder caught by gear type in NAFO Divisions 4RST in nine periods covering 1976 to 2016. Catches-at-length were weighted by the landings associated with each sample.

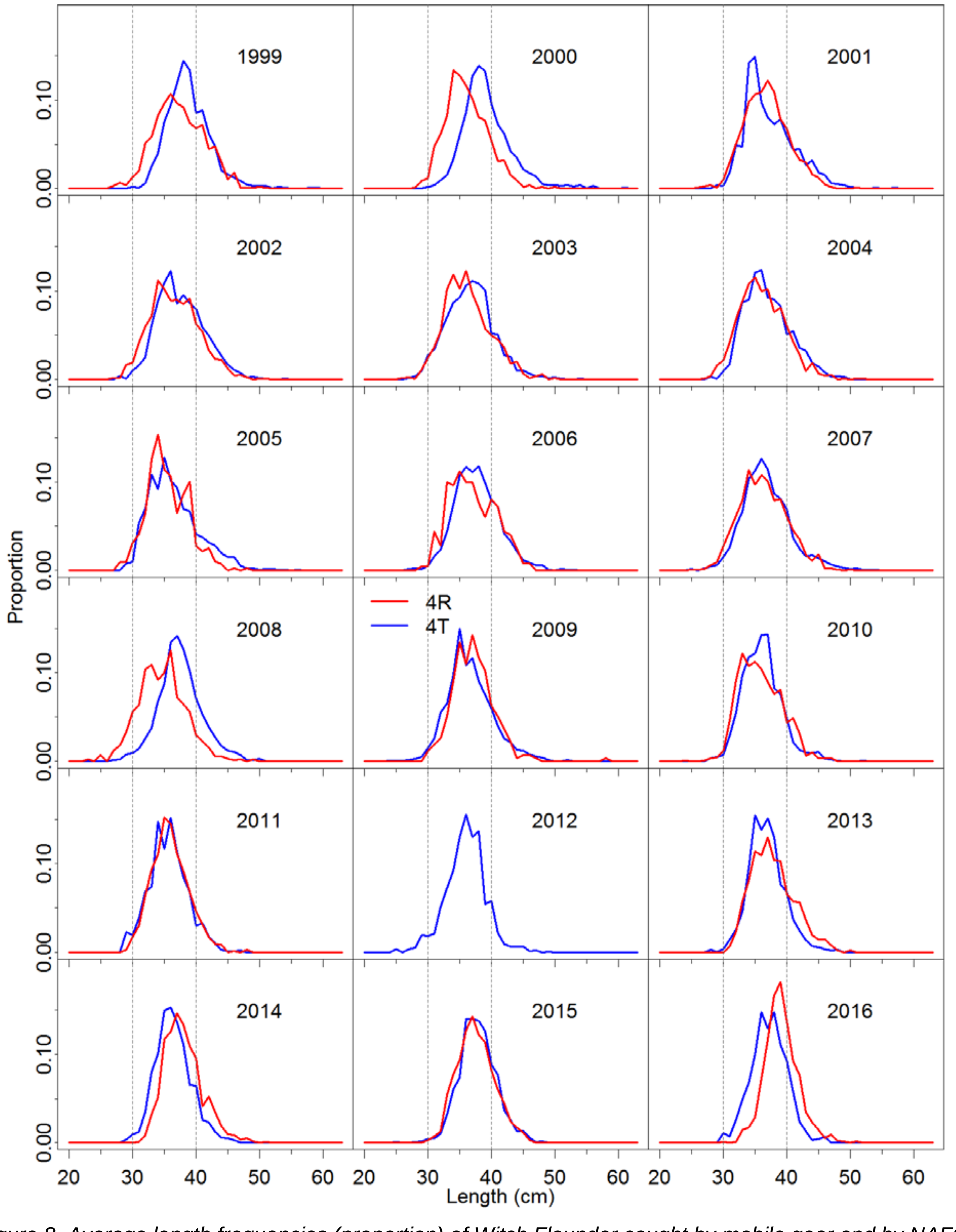

Figure 8. Average length frequencies (proportion) of Witch Flounder caught by mobile gear and by NAFO Division in NAFO Divisions 4RST for the period 1999-2016. Catches-at-length were weighted by the landings associated with each sample.

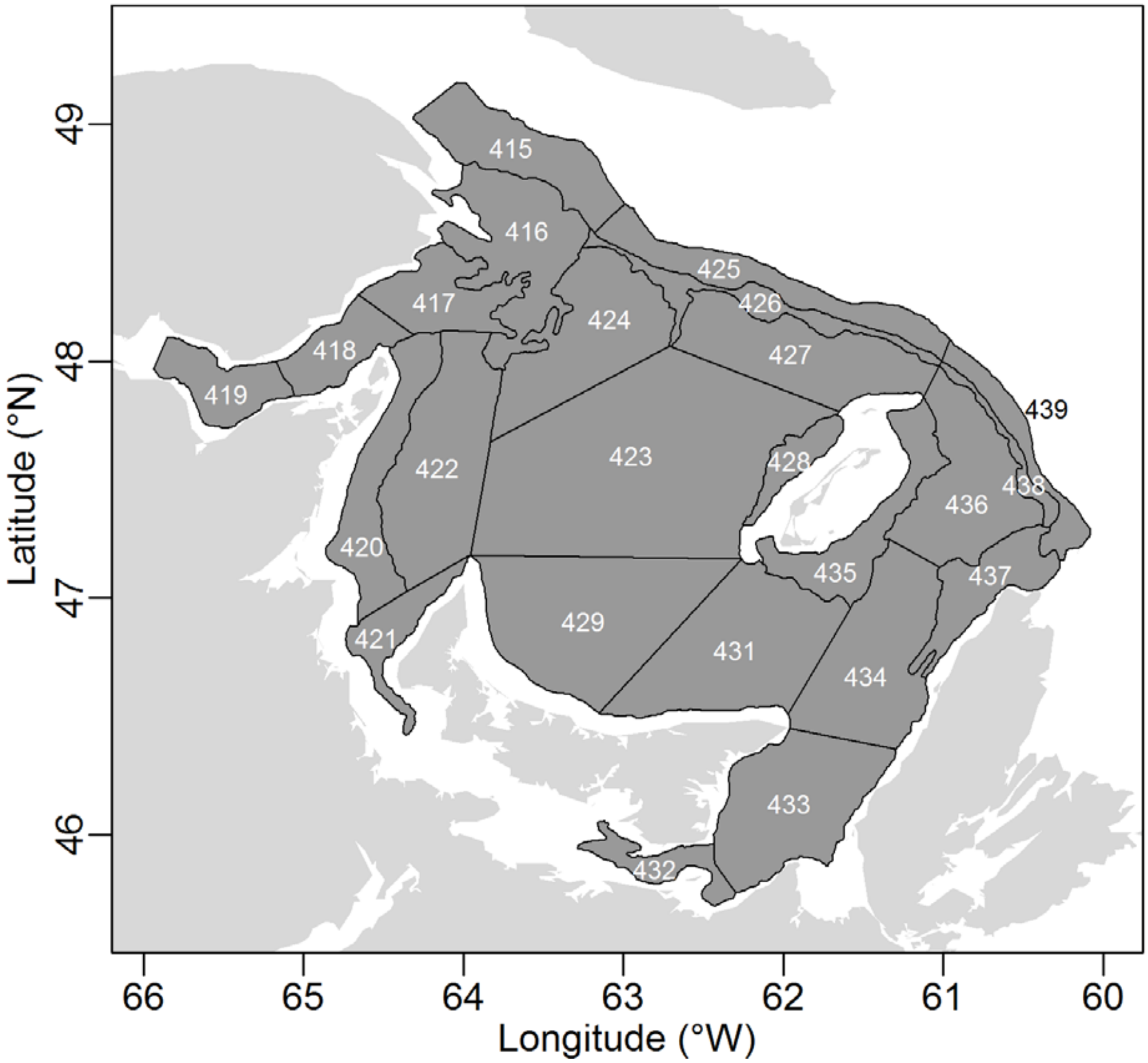

Figure 9. Stratum boundaries for the September bottom trawl survey of the southern Gulf of St. Lawrence. The strata appearing on the map are those used in the analyses.

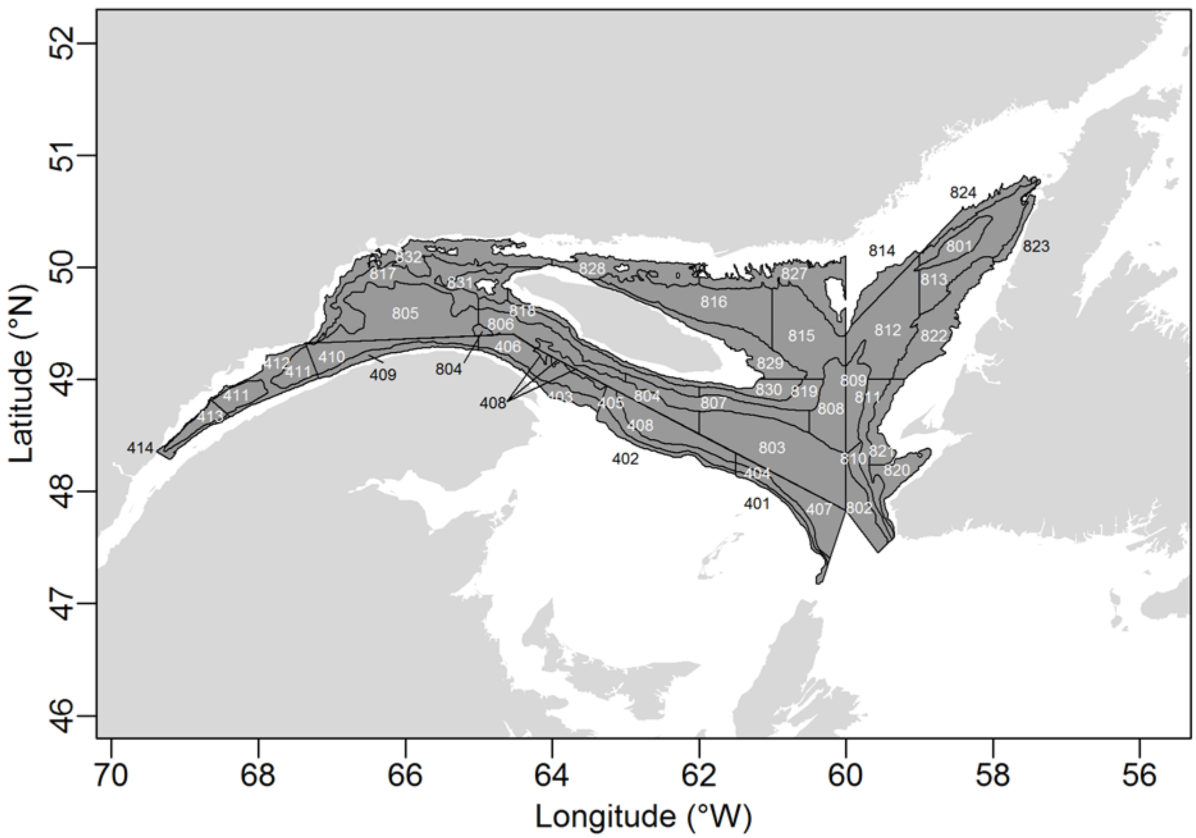

Figure 10. Stratum boundaries for the August bottom trawl survey of the northern Gulf of St. Lawrence. The strata appearing on the map are those used in the analyses.

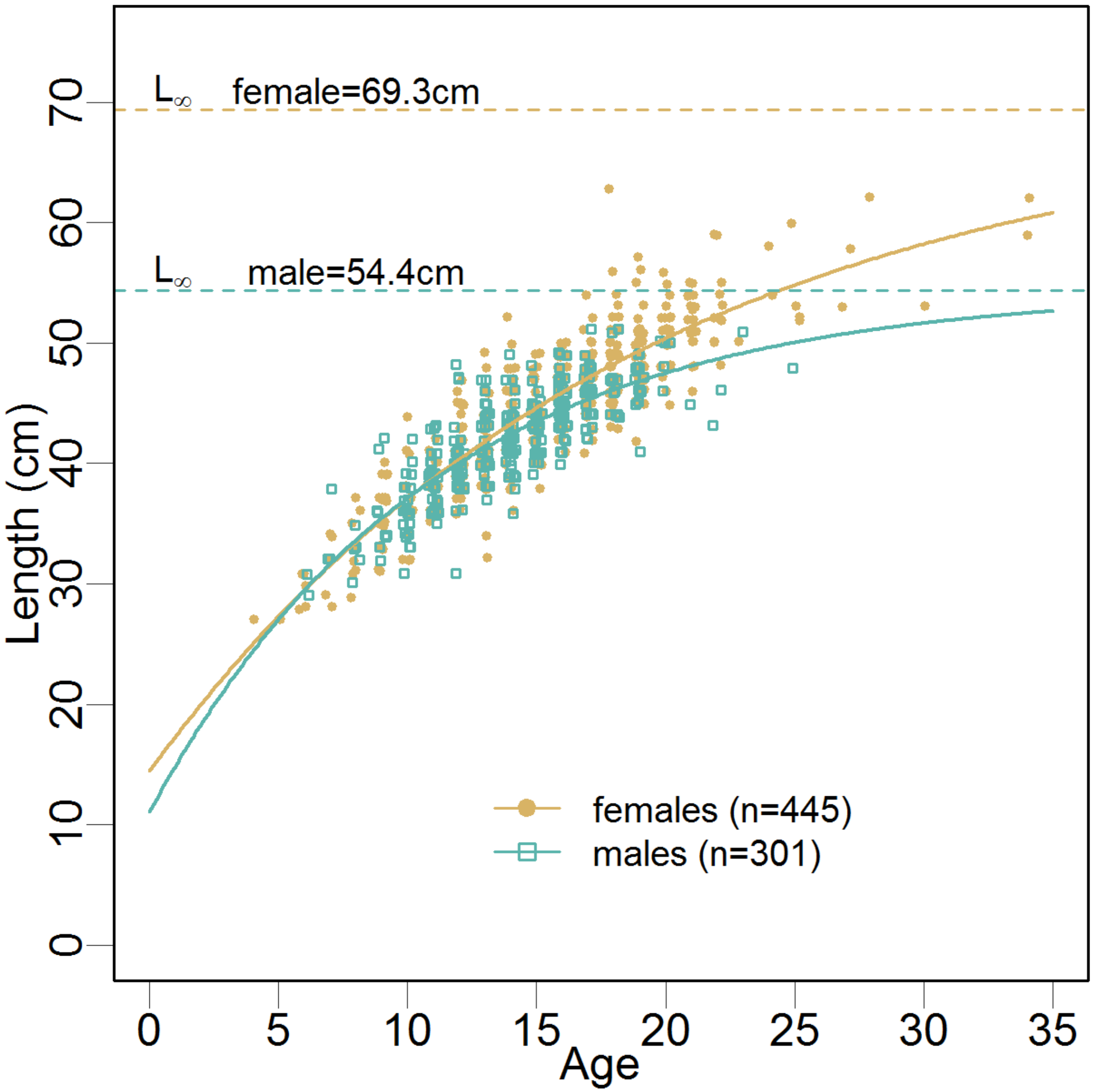

Figure 11. Von Bertallanfy estimates of growth of Witch Flounder by sex based on samples collected from the southern Gulf of St. Lawrence in September, 1974-1981.

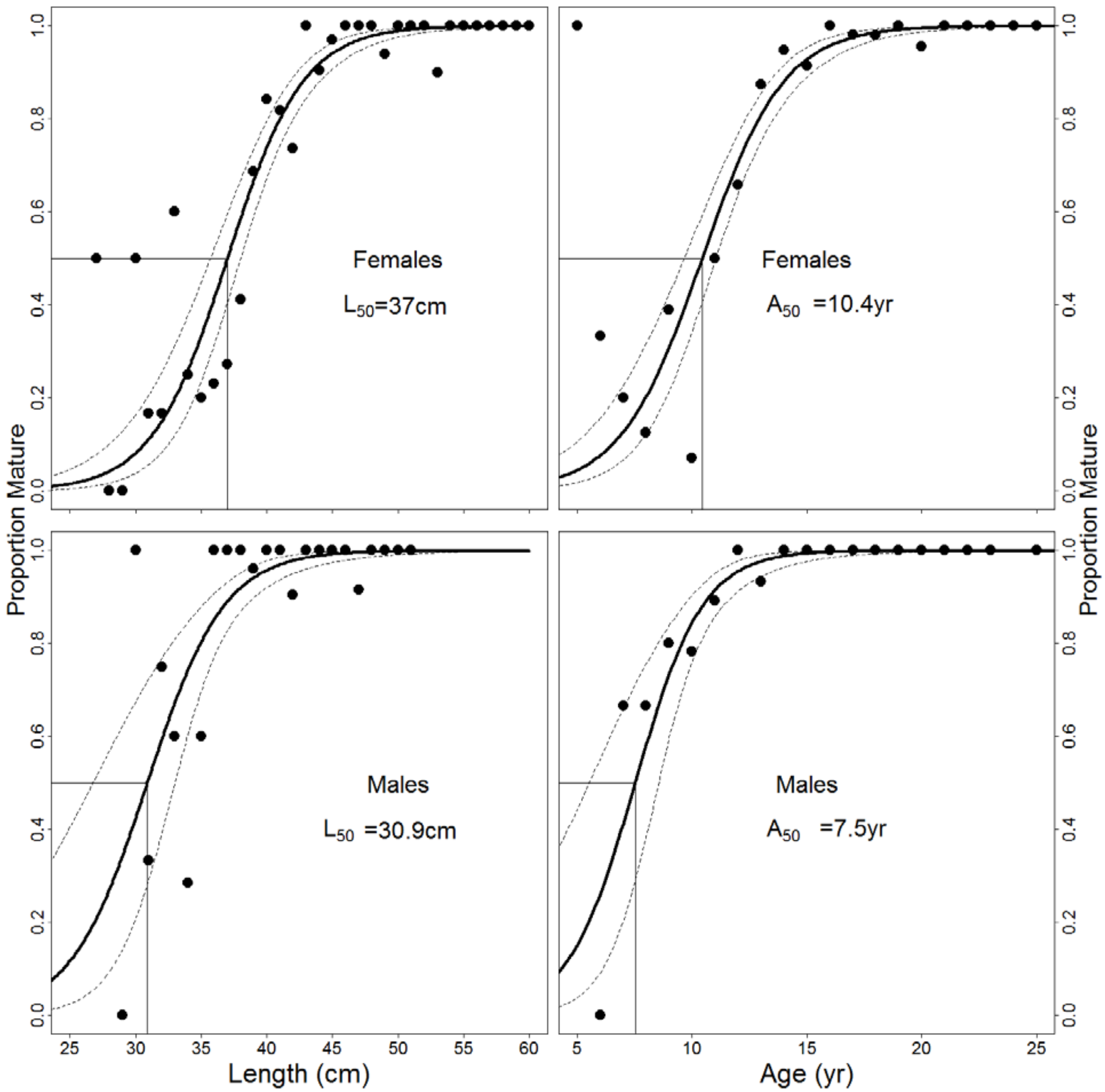

Figure 12. Maturity ogives by sex for Witch Flounder based on September survey data, 1970 to 1982. Circles are the observed proportions at length (left panels) or age (right panels) for females (top panels) and males (bottom panels). The solid lines show the fitted logistic regression models and the dashed lines show the confidence intervals around the predictions. The predicted lengths and ages at 50% maturity (L50 and A50) for males and females appear in each panel.

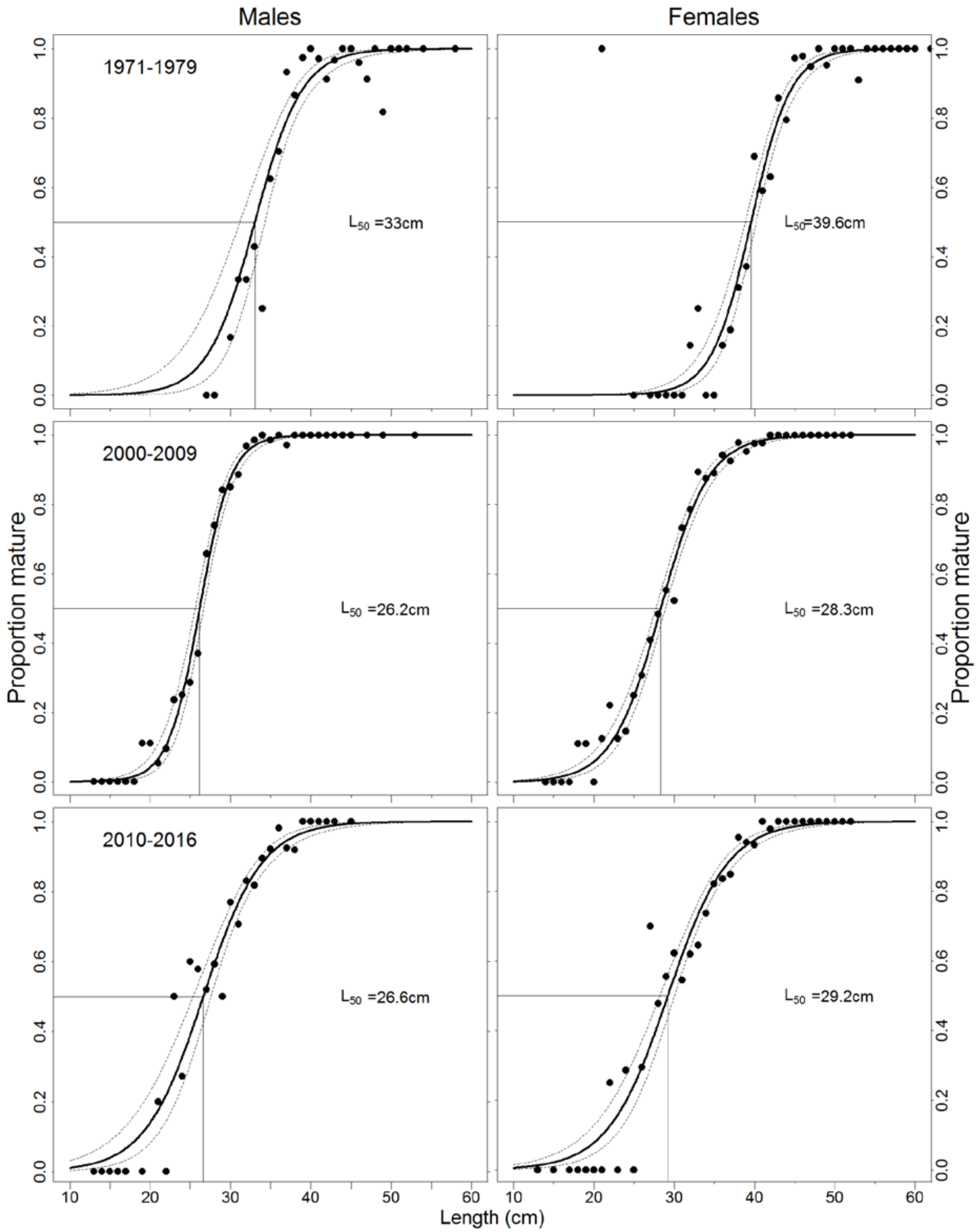

Figure 13. Maturity ogives by sex for Witch Flounder based on September survey data from the southern Gulf of St. Lawrence. The predicted length at 50% maturity is presented for males (left column) and females (right column) for the period 1970 to 1979 (top row), 2000 to 2009 (middle row) and 2010 to 2016 (bottom row).

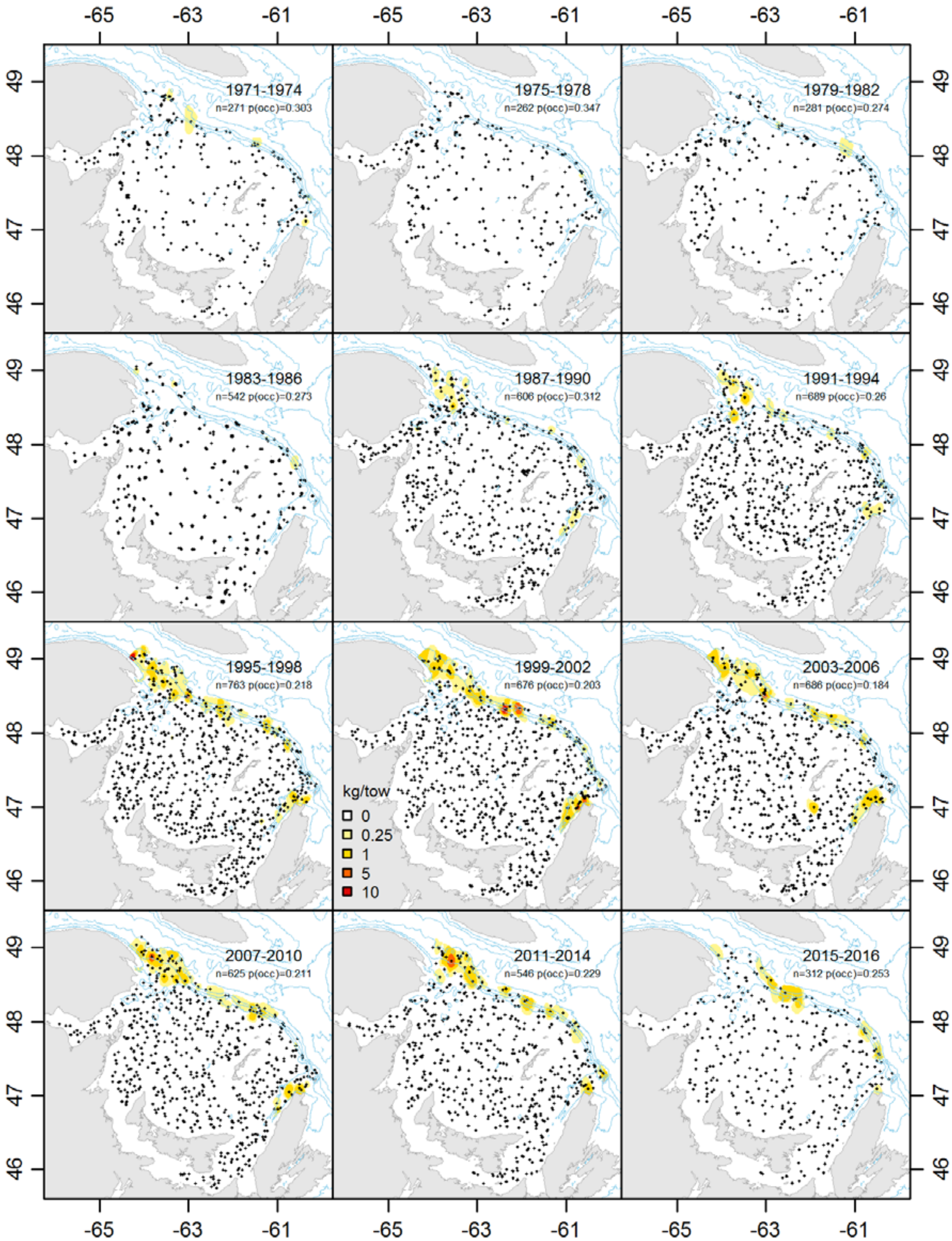

Figure 14. Distribution of biomass of Witch Flounder <30 cm in length in the September surveys of the southern Gulf of St. Lawrence, 1971 to 2016.

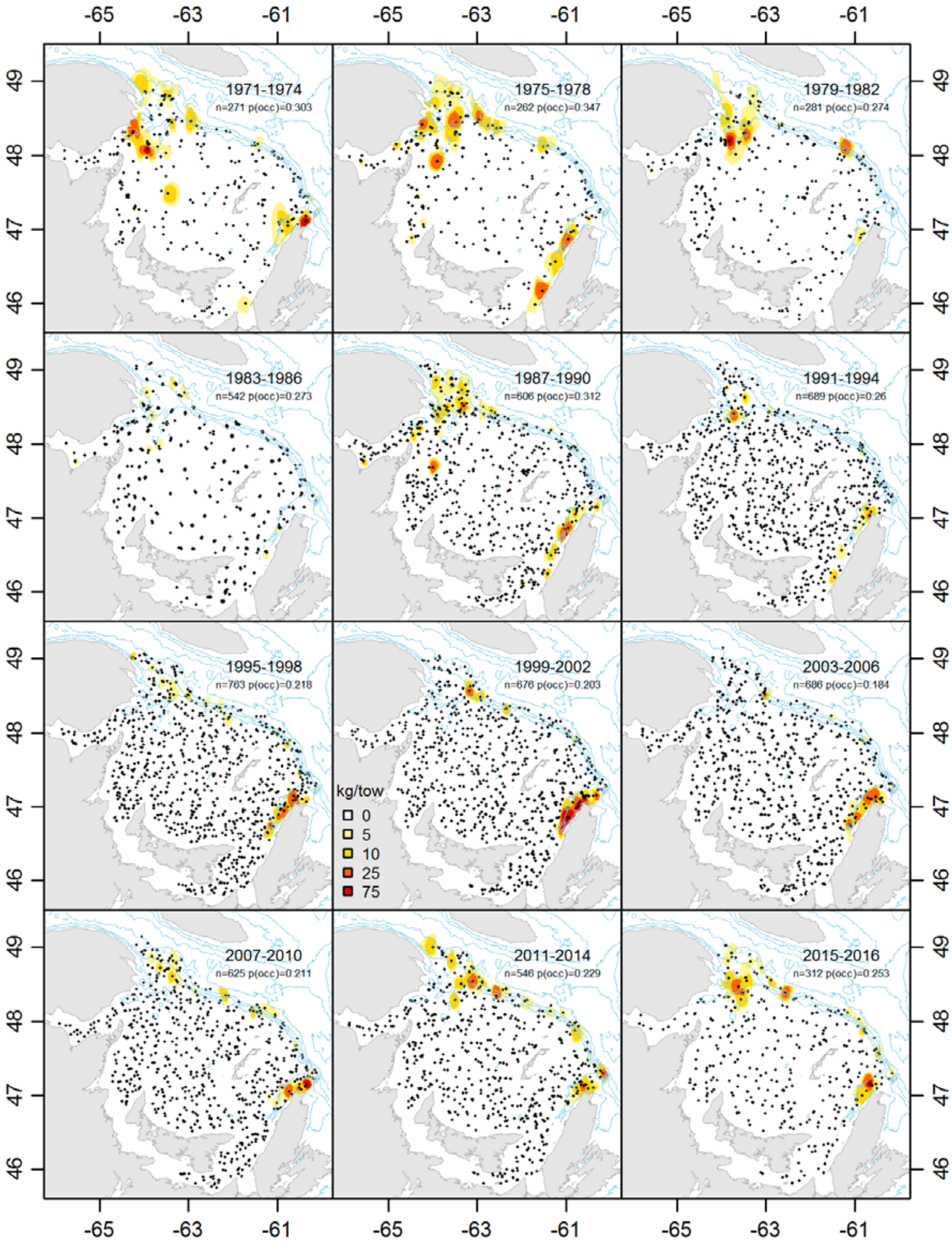

Figure 15. Distribution of biomass of Witch Flounder of 30+ cm in length in the September surveys of the southern Gulf of St. Lawrence, 1971 to 2016.

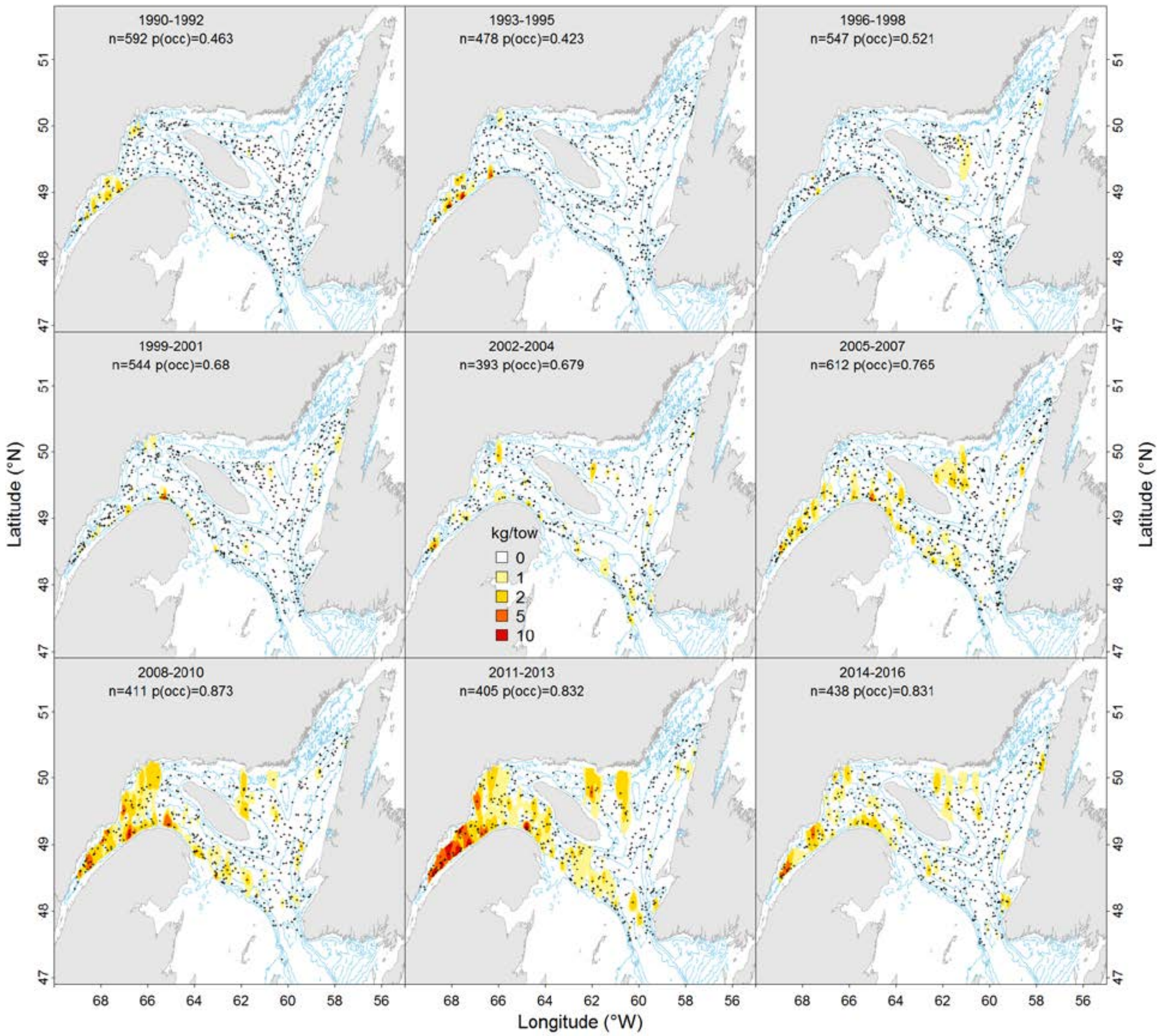

Figure 16. Distribution of biomass of Witch Flounder <30 cm in length in August surveys of the northern Gulf of St. Lawrence, 1990 to 2016.

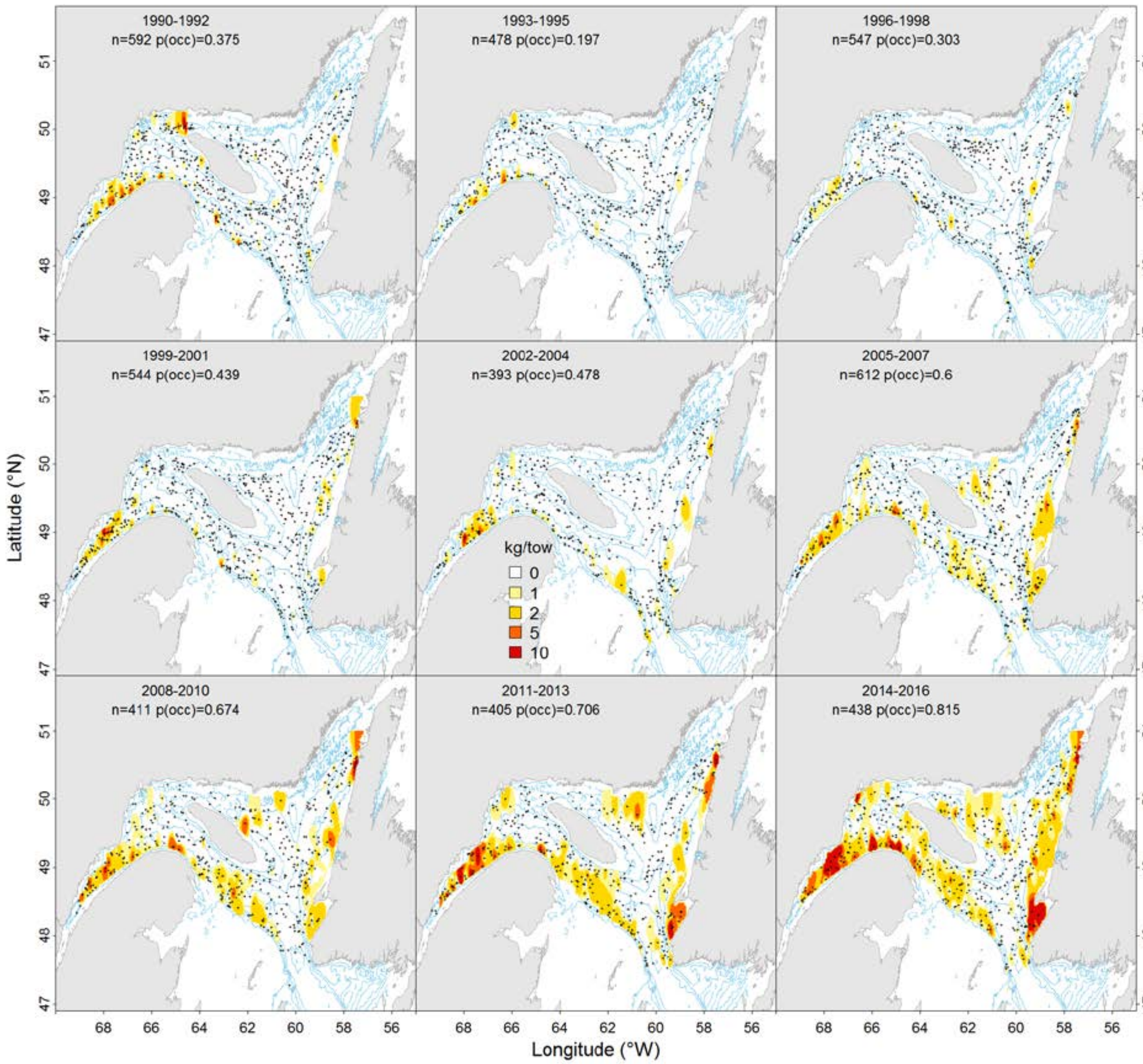

Figure 17. Distribution of biomass of Witch Flounder of 30+ cm in length in the August surveys of the northern Gulf of St. Lawrence, 1990 to 2016.

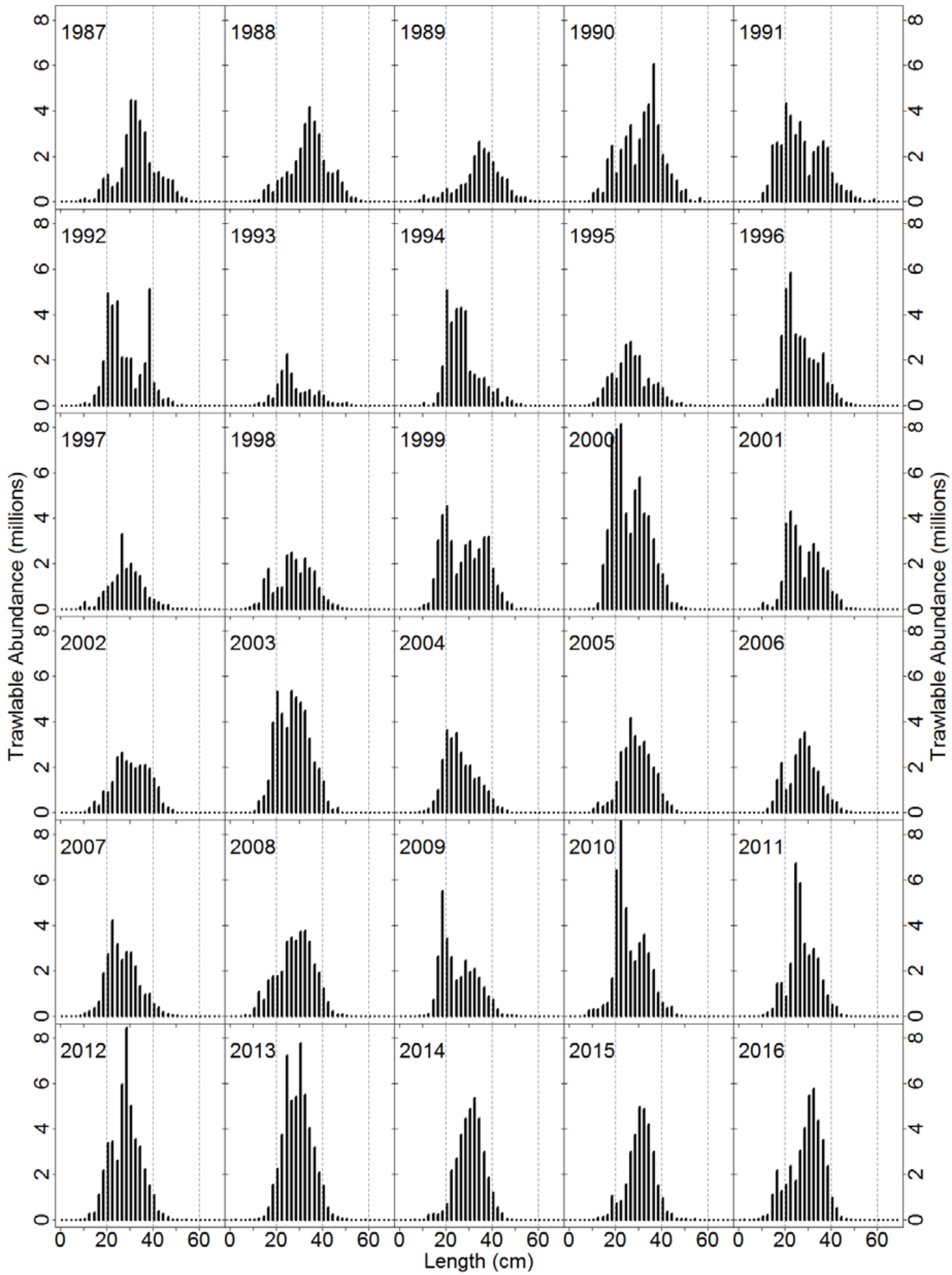

Figure 18. Length distributions of Witch Flounder caught in the August and September surveys of the Gulf of St. Lawrence, 1987 to 2016. Catches were adjusted to a night tow of 1.75 nm by the Lady Hammond using a Western IIA trawl.

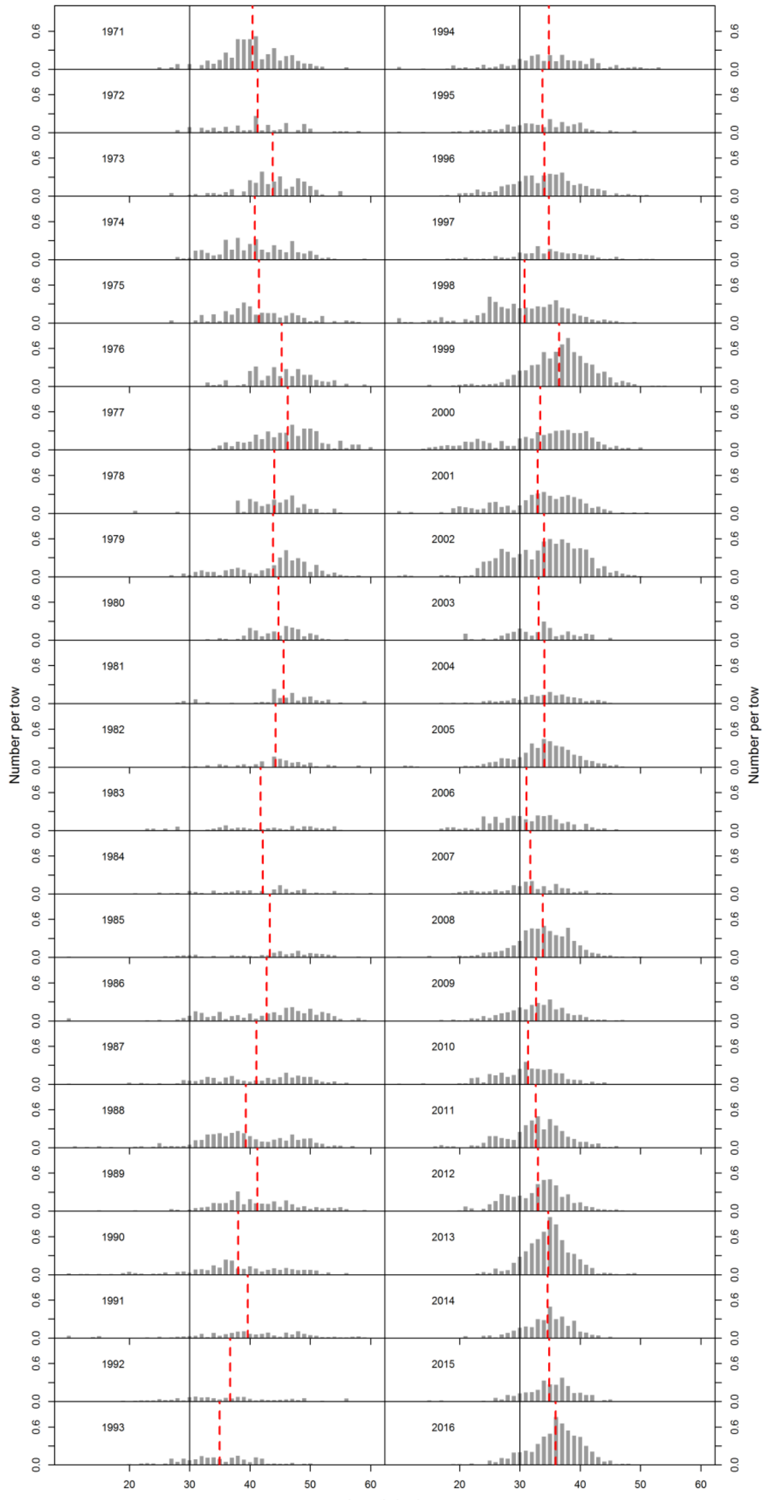

Figure 19. Length distributions of Witch Flounder caught in the September survey of the southern Gulf of St. Lawrence, 1971 to 2016. Catches are adjusted to a night tow of 1.75 nm by the Lady Hammond using a Western IIA trawl.

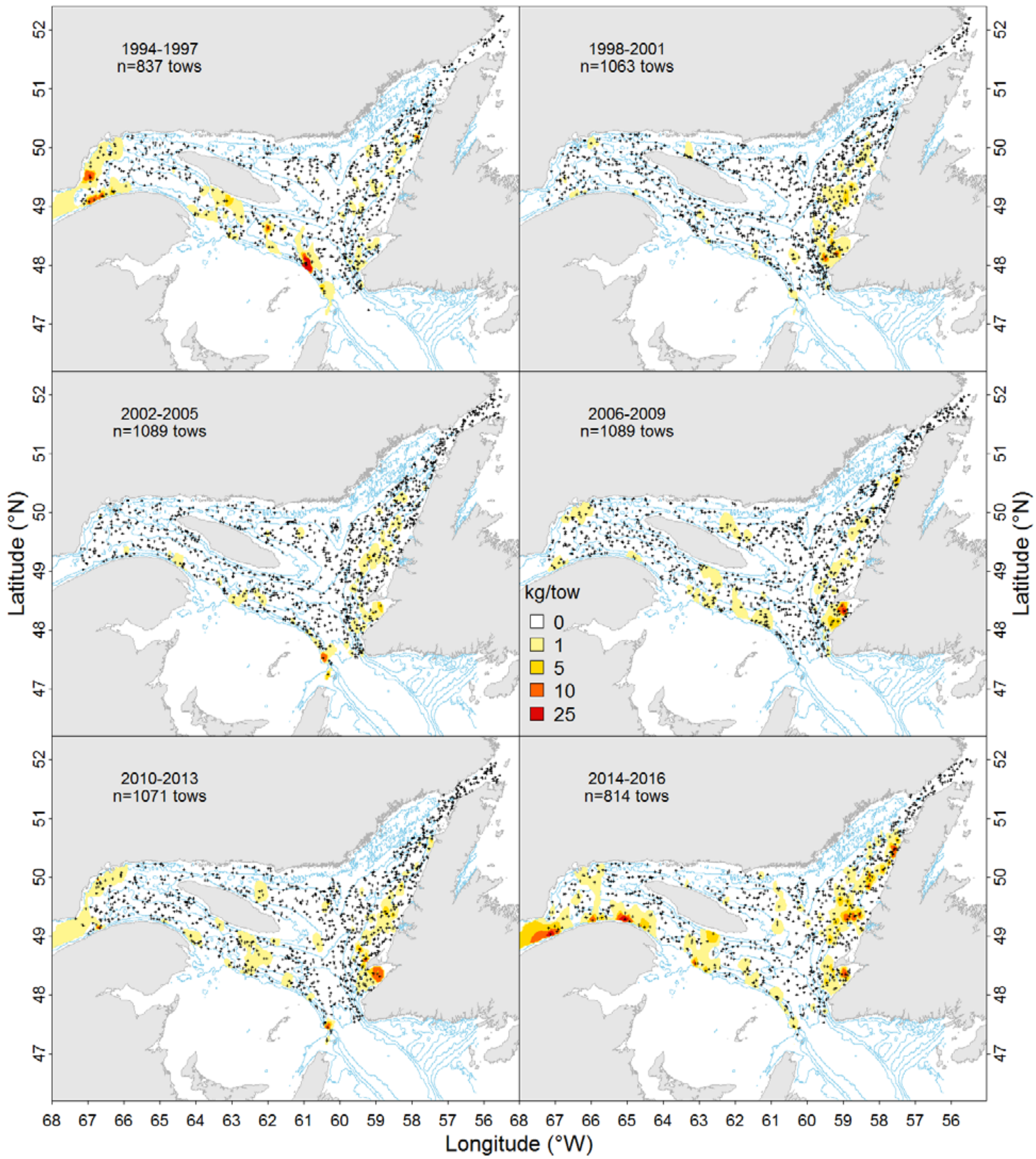

Figure 20. Distribution of biomass of Witch Flounder of 30+ cm in length in the summer sentinel surveys of the northern Gulf of St. Lawrence, 1994 to 2016.

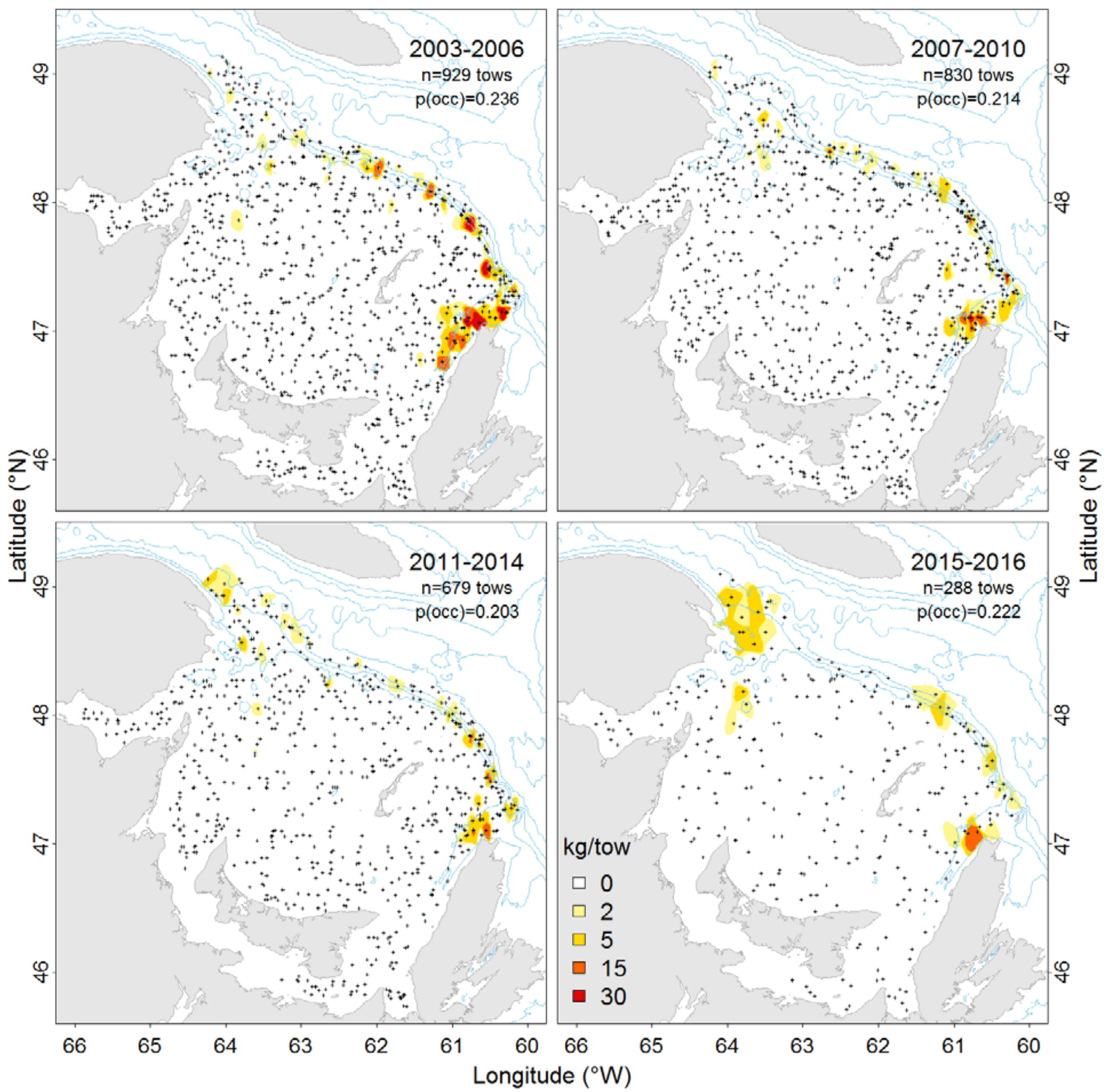

Figure 21. Distribution of biomass of Witch Flounder of 30+ cm in length in the summer sentinel surveys of the southern Gulf of St. Lawrence, 1994 to 2016.

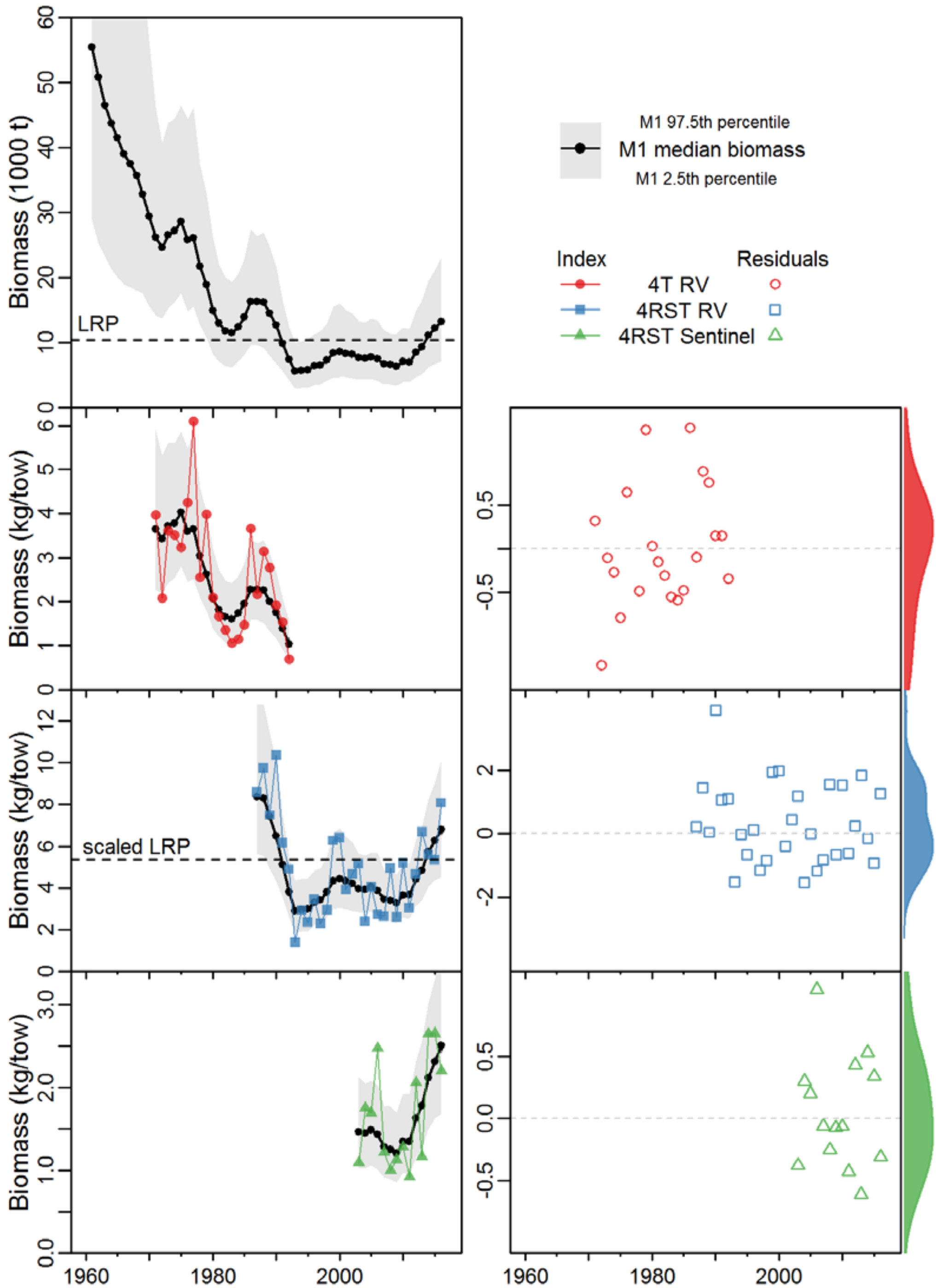

Figure 22. Estimated 30+ cm biomass from the single productivity surplus production model M1 of NAFO Div. 4RST Witch Flounder (top left panel), comparison of catchability-corrected predicted indices and observed indices (bottom three left panel) and residuals between observations and predictions for the three indices used (bottom three right panel).The median 30+ cm estimated biomass appears as a solid black line with black dots and the 2.5th and 97.5th percentiles define the grey polygon around the median. The limit reference point (LRP=0.4Bmsy) is shown for both the 30+ cm biomass and for the 4RST RV index.

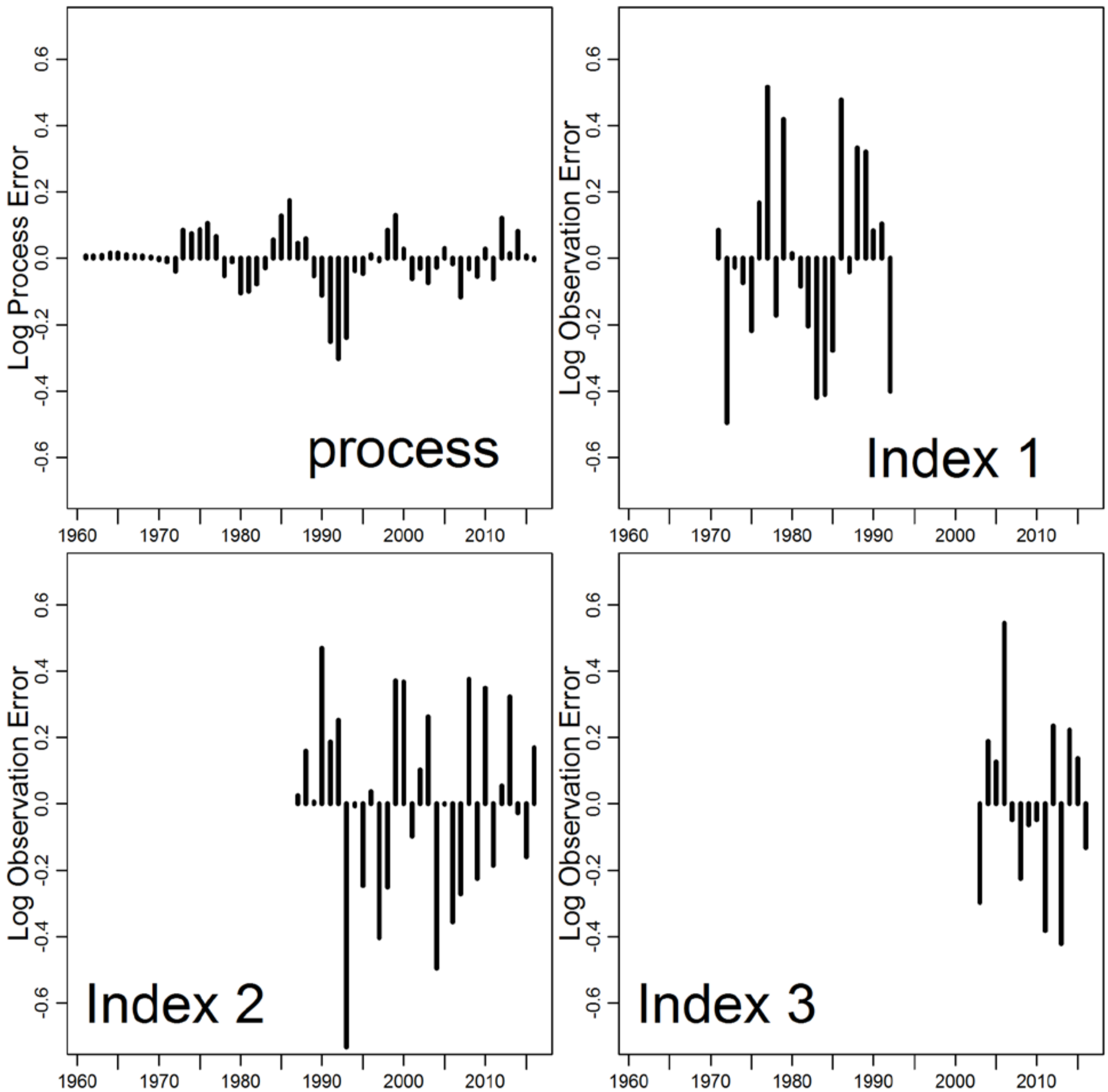

Figure 23. Process and observation errors for the single productivity surplus production model M1 of NAFO Div. 4RST Witch Flounder.

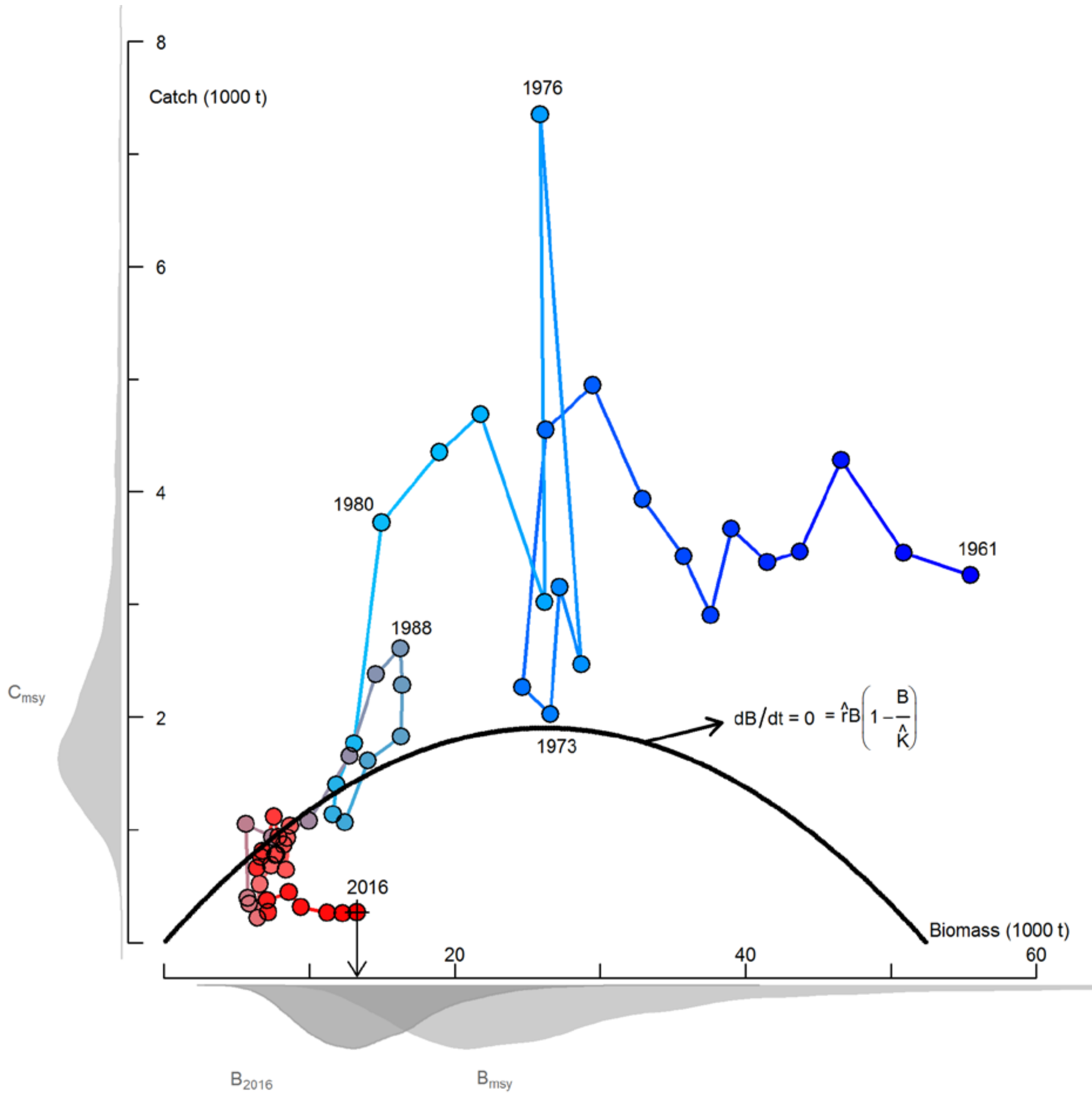

Figure 24. Observed NAFO Div. 4RST Witch Flounder catch as a function of the 30+ cm biomass estimated from the Schaefer surplus production model for the single productivity regime model M1.The temporal evolution of both the catch and the estimated biomass is colour-coded from blue (earliest years) to red (latest years). The solid black line indicates the model-derived catch levels at different biomass levels that result in no changes in biomass from year to year. Based on the Schaefer model structure, points located above the solid black line will lead to decreasing biomass over time and points located below the line will lead to increasing biomass over time. The posterior probability distribution of the catch at maximum sustainable yield (C_{msy}) is shown on the outer margin of the y-axis. The posterior probability distributions of the biomass that generates the maximum sustainable yield (B_{msy}) and the biomass in 2016 (B_{2016}) are shown on the outer margin of the x-axis.

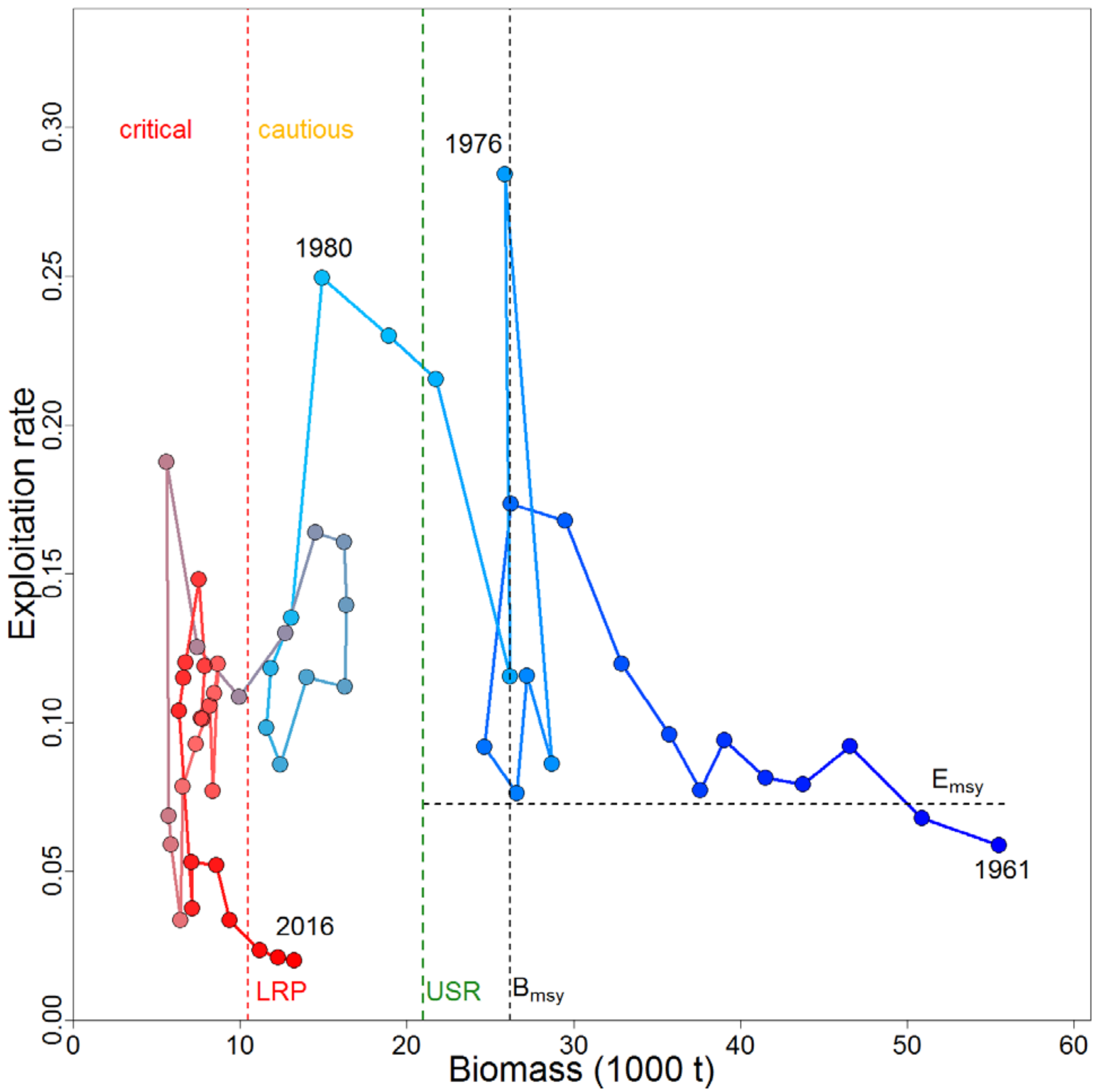

Figure 25. Precautionary approach plot for NAFO Div. 4RST Witch Flounder. The x axis shows the biomass of Witch Flounder for the period 1961 to 2016 as estimated by the Bayesian Surplus Production Schaefer Model. Also shown on the x axis are the Limit Reference Point (LRP, 40% of B_{msy}), the Upper Stock Reference (USR, 80% of B_{msy}) and the biomass at Maximum Sustainable Yield (B_{msy}). The y axis shows the exploitation rate of Witch Flounder for the period 1961 to 2016 along with the exploitation rate at Maximum Sustainable Yield (E_{msy}). The temporal evolution of both the estimated biomass and the exploitation rate is colour-coded from blue (earliest years) to red (latest years).

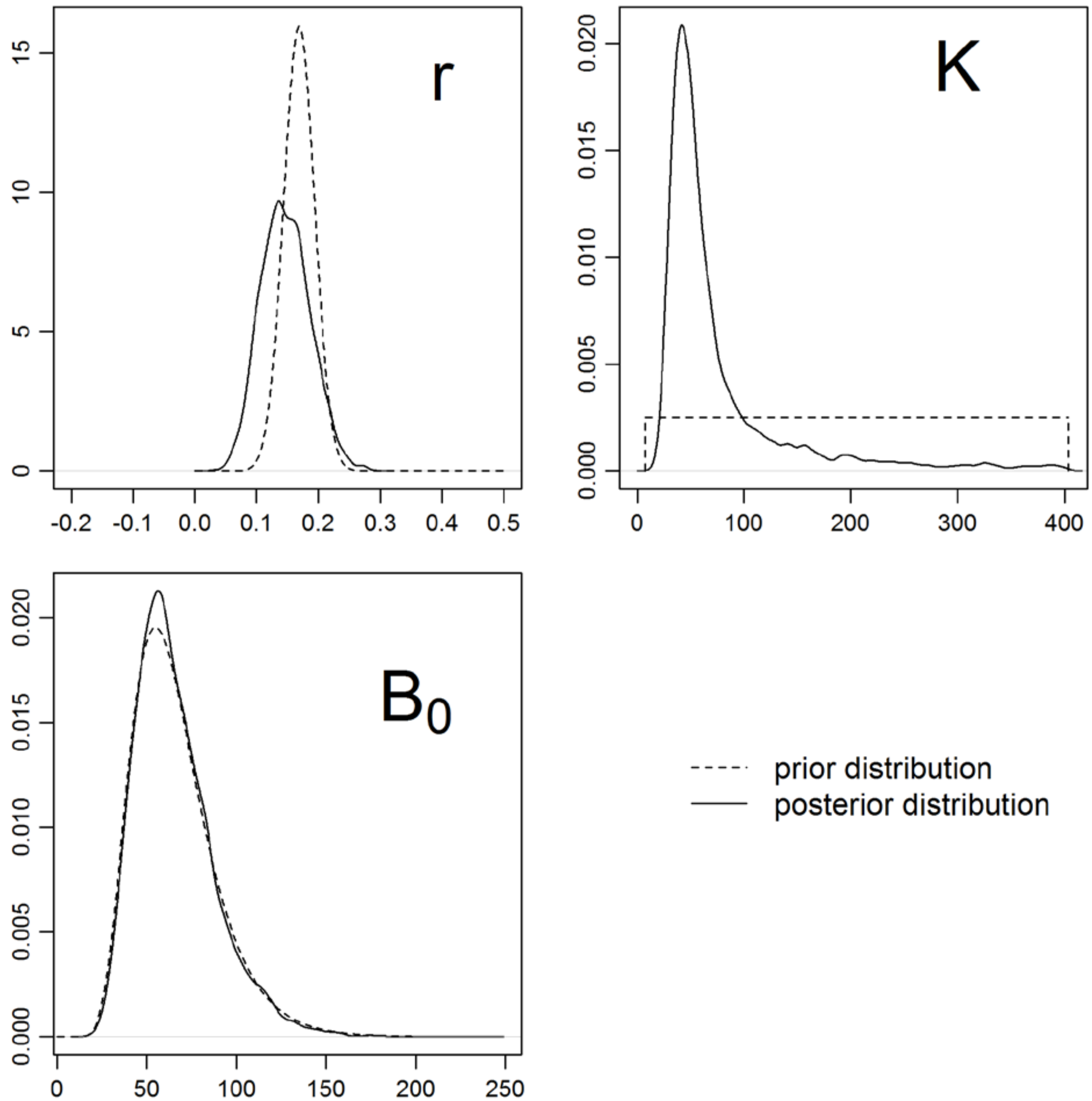

Figure 26. Prior (dashed lines) and posterior (solid lines) probability distributions of the intrinsic rate of increase r, carrying capacity K and starting biomass B0 for the single productivity regime model M1 of NAFO Div. 4RST Witch Flounder.

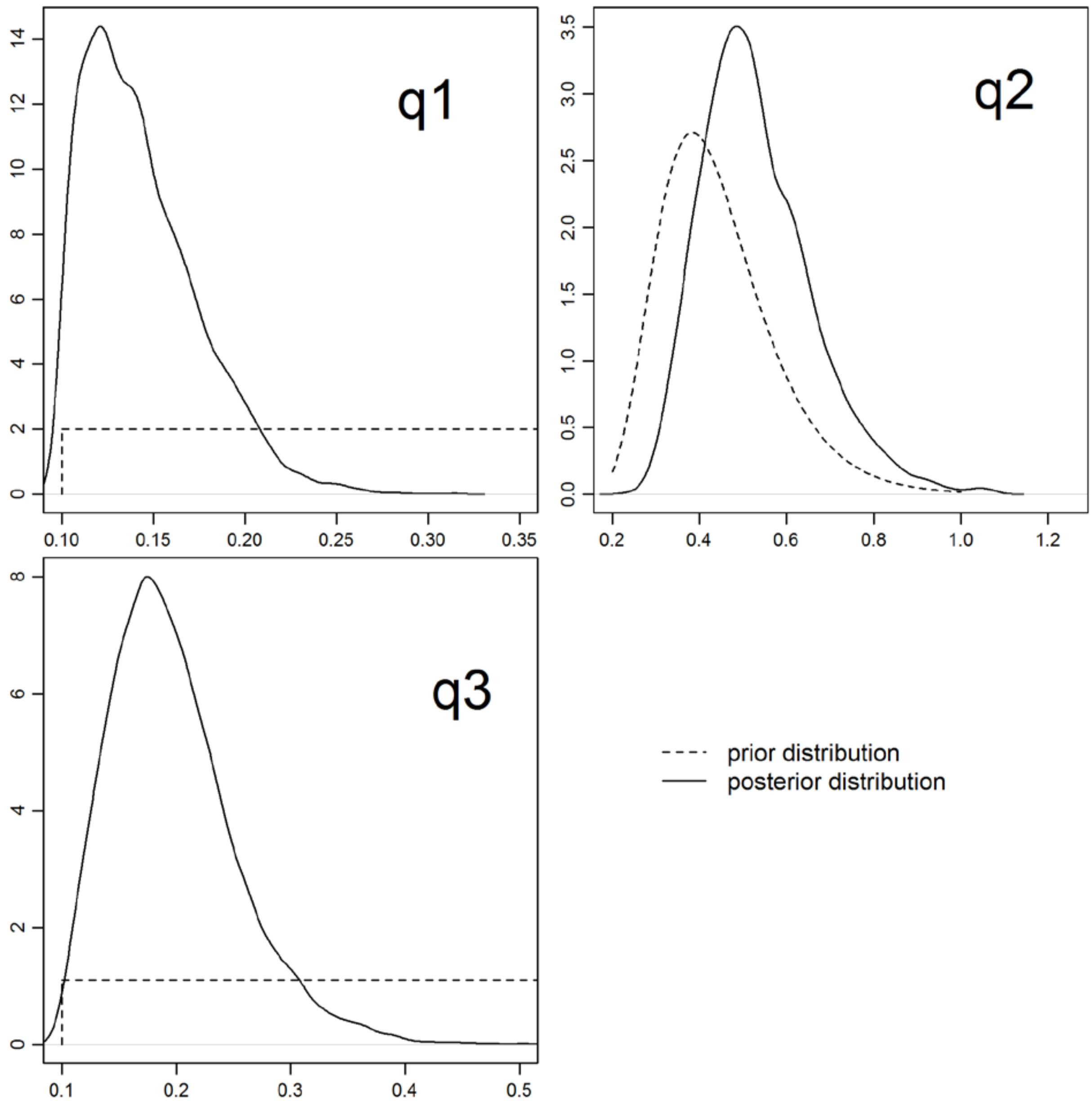

Figure 27. Prior (dashed lines) and posterior (solid lines) probability distributions of the catchability to indices 1, 2 and 3 for the single productivity regime model M1 of NAFO Div. 4RST Witch Flounder.

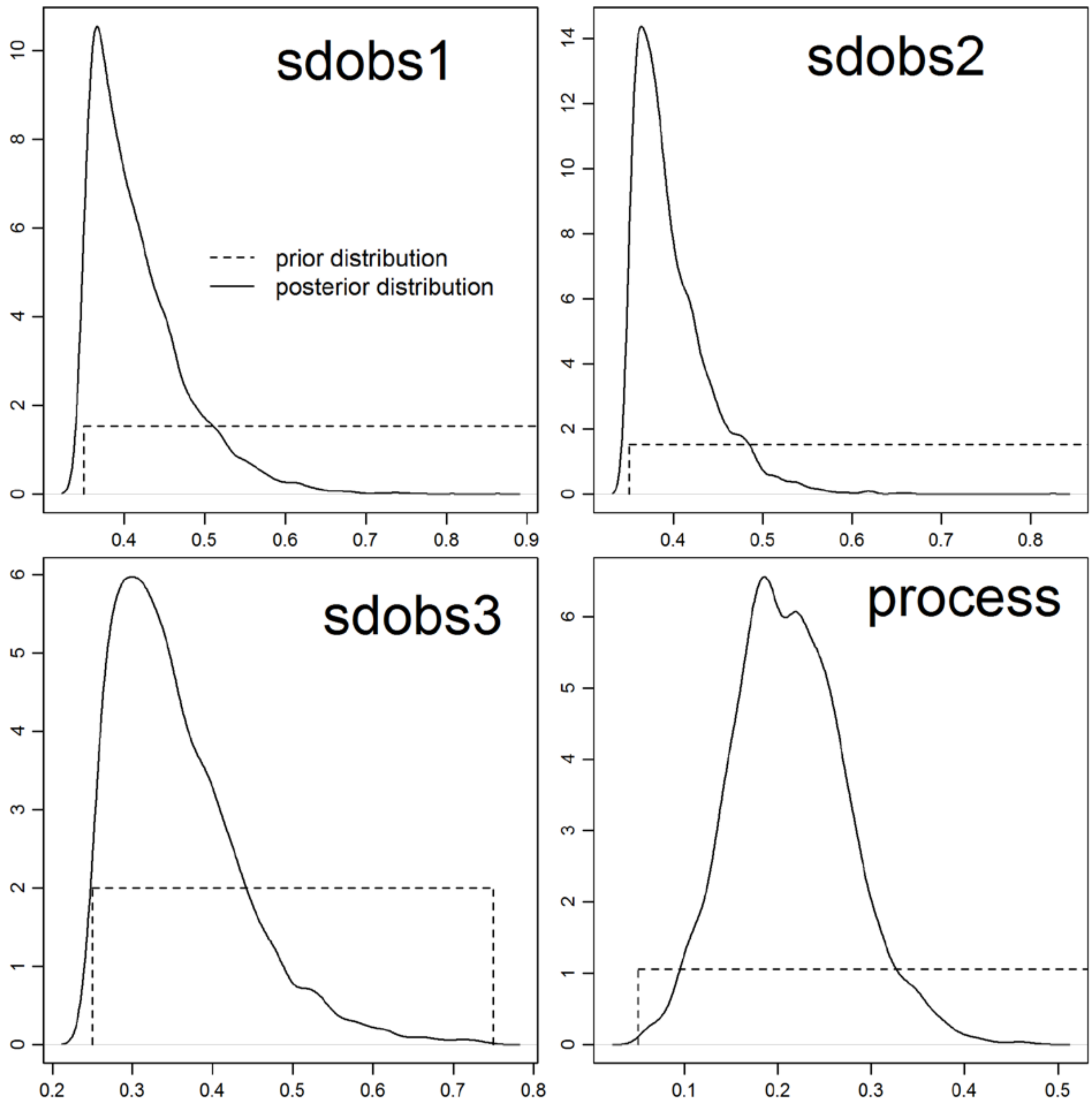

Figure 28. Prior (dashed lines) and posterior (solid lines) probability distributions of the standard deviations of observation and process error for the single productivity regime model M1 of NAFO Div. 4RST Witch Flounder.

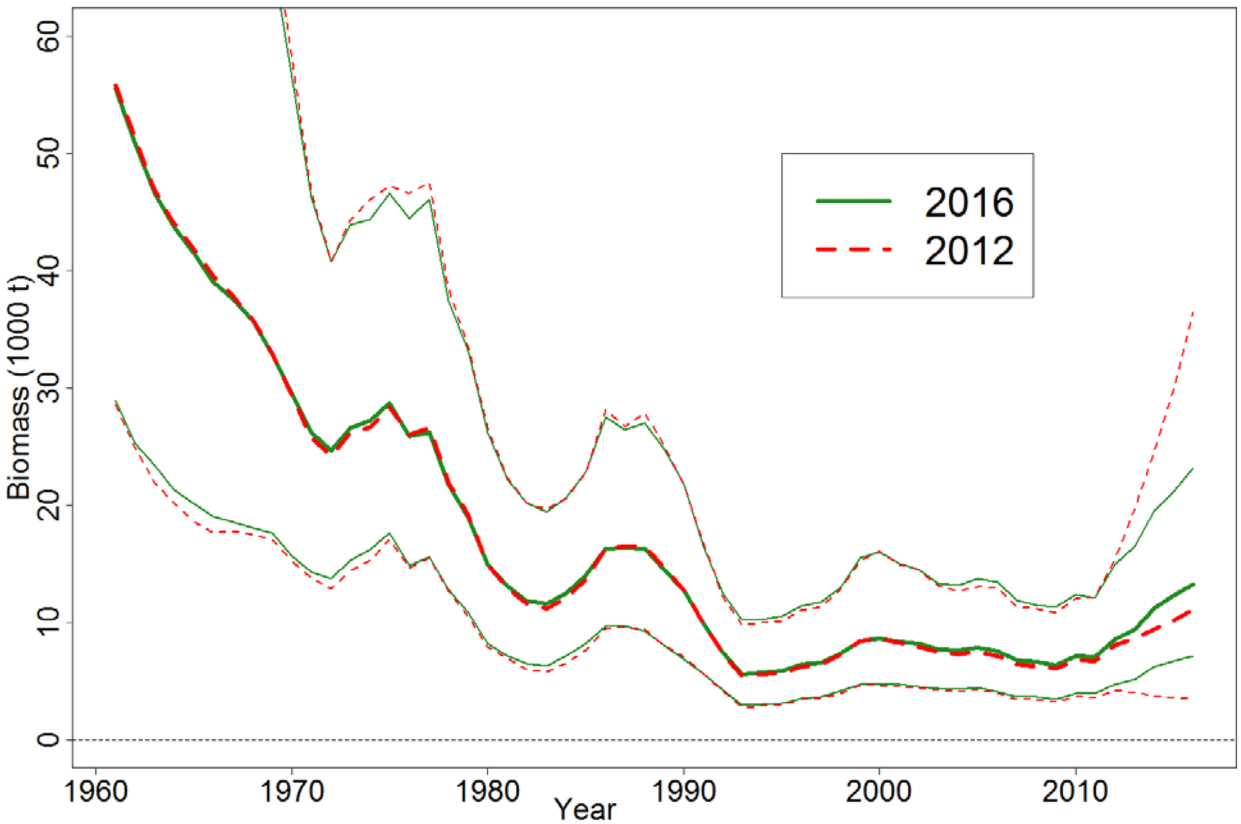

Figure 29. Estimated 30+ cm biomass of Witch Flounder in NAFO Div. 4RST obtained by fitting the single productivity regime Schaefer model M1 with all the biomass index data (solid green line) and by omitting the last 4 years of index data (dashed red line).Heavy lines are the median estimates and thin lines show the 2.5th and 97.5th quantiles.

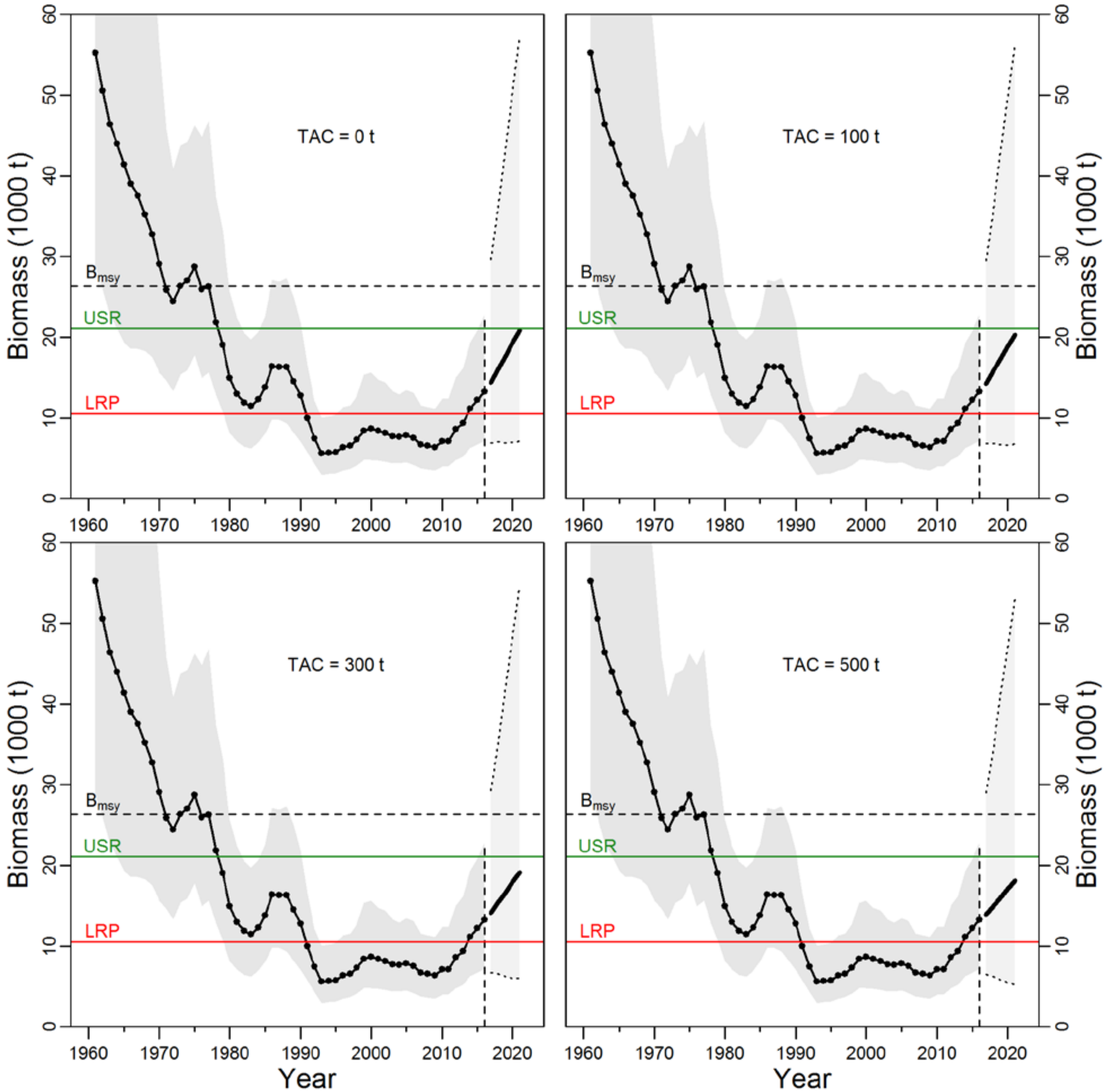

Figure 30. Projected 30+ cm biomass (kt) of NAFO Div. 4RST Witch Flounder at various annual catch levels in 2017 to 2021 (0 t panel a, 100 t panel b, 300 t panel c and 500 t panel d) using the single productivity regime model M1. In panels a-d, the solid black lines are the posteriors medians and the grey polygon spans the 2.5th and the 97.5th quantiles. Biomasses for years 2017 to 2021 are projected estimates. The red horizontal lines show the limit reference point (LRP) which corresponds to 40% of B_{msy}, the green horizontal lines show the Upper Stock Reference (USR) which corresponds to 80% of B_{msy}, and the horizontal dashed black lines show B_{msy}.

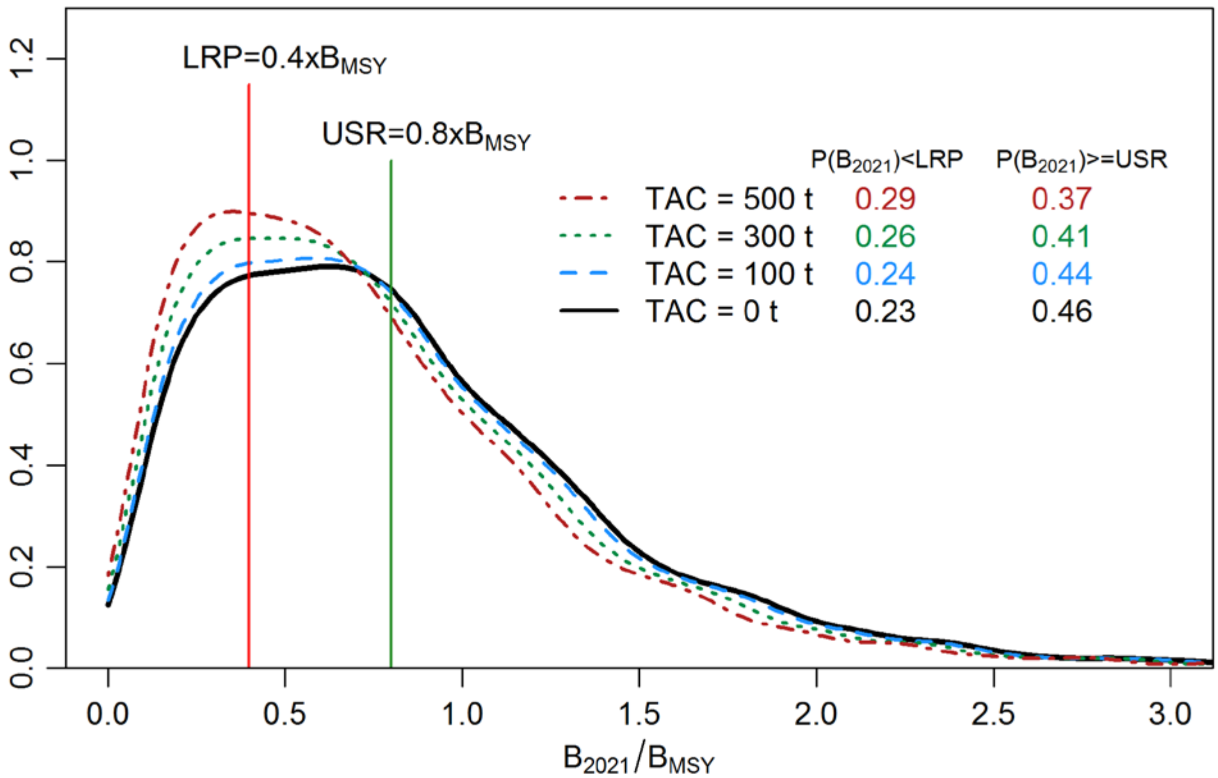

Figure 31. Estimated biomass in 2021 of NAFO Div. 4RST Witch Flounder as a proportion of B_{msy} at various annual catch levels for the period 2017 to 2021.

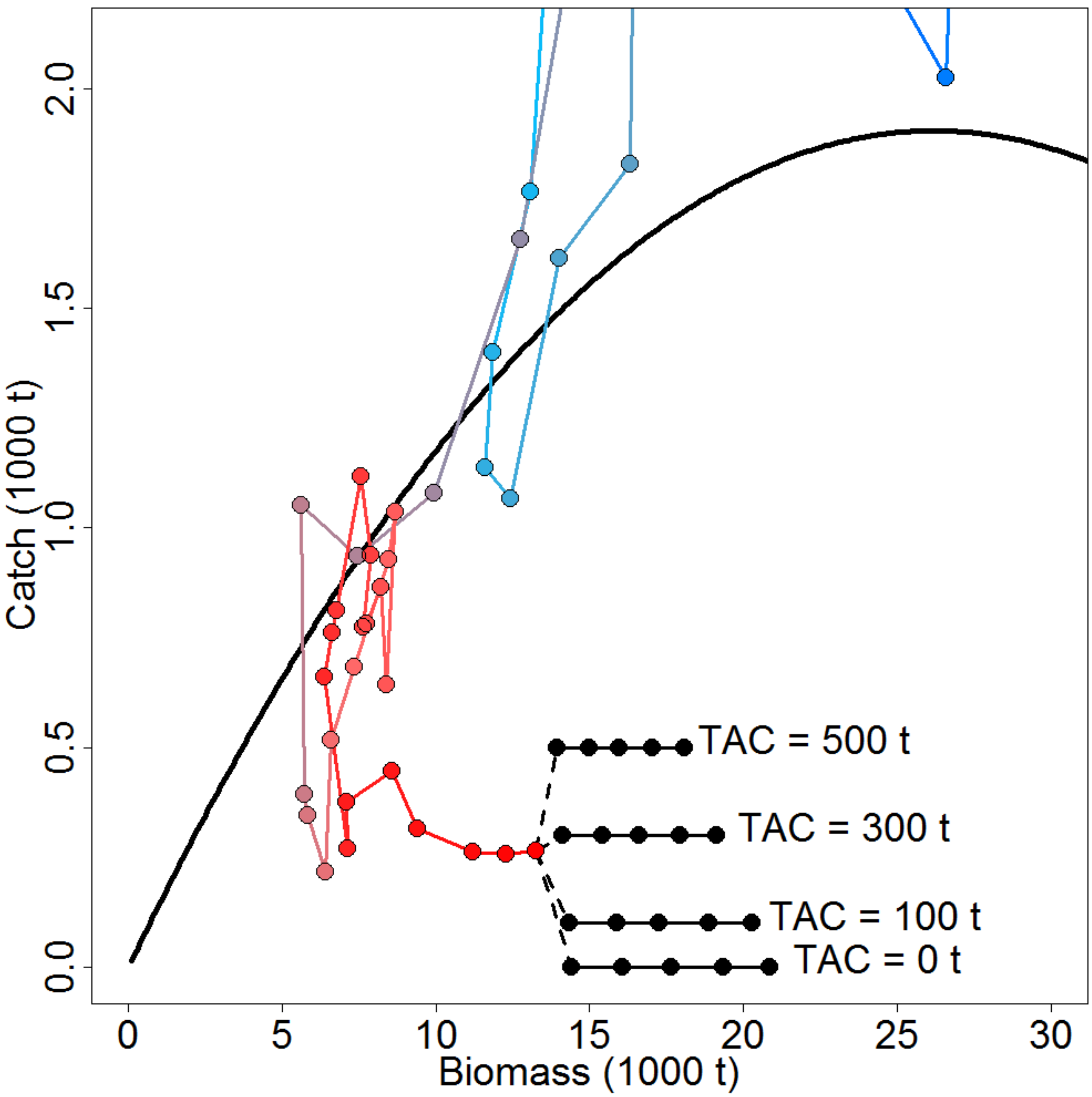

Figure 32. Projected 30+ cm biomass (kt) of NAFO Div. 4RST Witch Flounder at various annual catch levels in 2017 to 2021.The last red point corresponds to the catch and the estimated 30+ cm biomass in 2016.

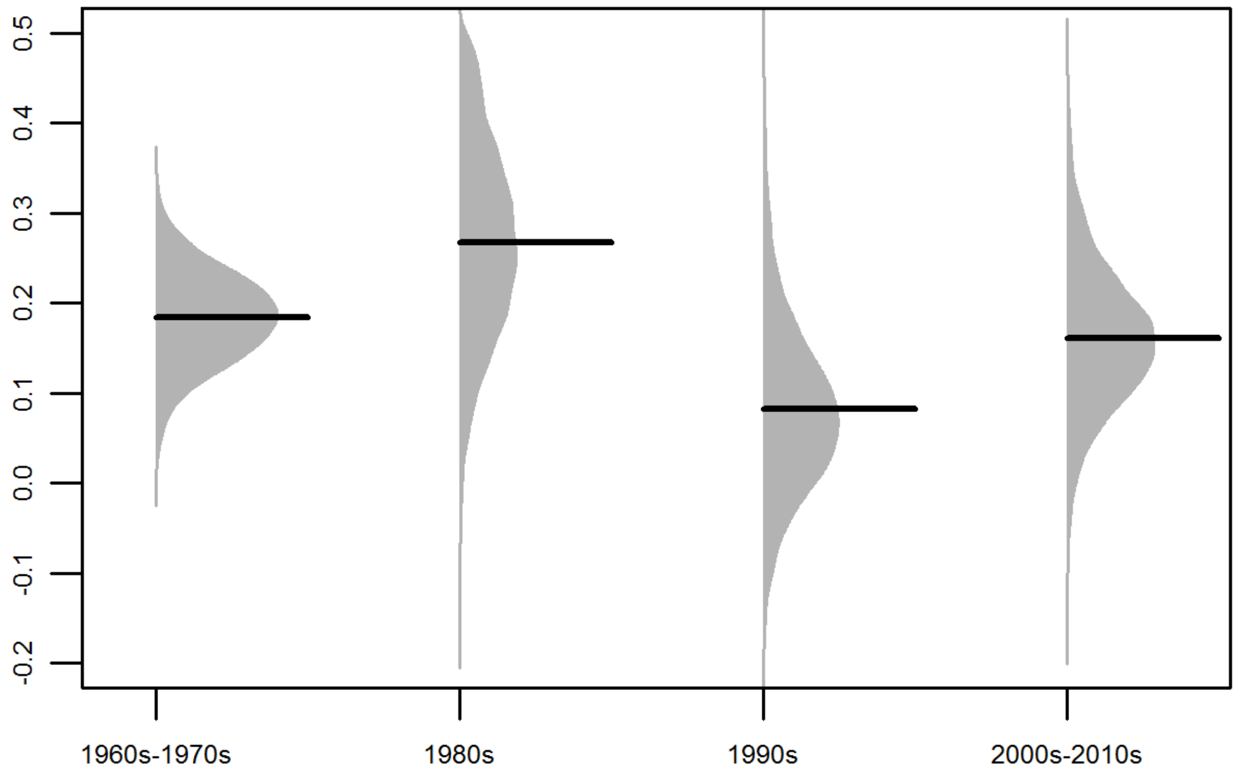

Figure 33. Beanplots showing the posterior distributions for r for the Schaefer surplus production model for NAFO Div. 4RST Witch Flounder allowing decadal variations in r.

APPENDICES

APPENDIX A. METHODOLOGICAL DETAILS OF THE COMPUTATION OF A GULF-WIDE INDEX FOR NAFO 4RST WITCH FLOUNDER

In the previous assessments of the NAFO Divisions 4RST Witch Flounder population, much analytical work was directed at computing indices of population abundance and biomass that represent the status of the population as a whole. This task involves adjusting the catch data obtained from a variety of vessel and gear combinations over the time series of two separate bottom trawl surveys and two separate sentinel surveys. The adjustments to be applied to the catch data are themselves estimated by analysing catch data from comparative fishing experiments where paired tows are conducted at shared locations by the two different sampling platforms. This Appendix details the methodological steps required to compute Gulf-wide abundance and biomass indices of Witch Flounder of various length groups, as presented in the stock assessment, and used to fit the Bayesian surplus production model that forms the basis of the assessment. The first part of this Appendix provides a historical summary of the different surveys conducted in the Gulf of St. Lawrence, including a description of the comparative fishing experiments that took place over the years. The methods used in the derivation of conversion factors for Witch Flounder are then presented along with the steps required to compute the single index for the entire Gulf of St. Lawrence used in the assessment.

Summary of Research Vessel (RV) Surveys in NAFO Divisions 4RST

Two separate research vessel surveys are conducted annually in the Gulf of St. Lawrence: 1) the northern Gulf survey conducted in August by the Quebec Region of Fisheries and Oceans Canada and 2) the southern Gulf survey conducted in September by the Gulf Region of Fisheries and Oceans Canada (Figure A1). A description of the timeline for both surveys is provided along with a description of the comparative fishing experiments that have taken place to estimate vessel, gear and diurnal effects on survey captures.

Northern Gulf of St. Lawrence RV surveys

The northern Gulf of St. Lawrence stratified random survey has been taking place in August since 1984. From 1984 to 1989, the survey platform was the *Lady Hammond* using a *Western IIA* trawl. From 1990 to 2003, the survey used the *Alfred Needler* with a *URI* shrimp trawl. Since 2004, the *Teleost* is the research vessel used with a *Campelen* trawl. Comparative fishing experiments took place in 1990 between the *Lady Hammond* and the *Alfred Needler* and again in 2004 and 2005 between the *Alfred Needler* and the *Teleost* (top panel of Figure A2). The 1990 comparative fishing experiments consisted in 80 paired tows conducted in the northern Gulf of St. Lawrence (Figure A3) while the 2004 and 2005 comparative fishing experiments had 10 and 159 paired tows, respectively (Figure A4).

The target tow duration has also changed over the history of the northern Gulf survey. The target fishing procedure was a 30-min tow at 3.5 knots in 1984 to 1989 (standard tow=1.75 nautical miles), a 20-min tow at 2.5 knots in 1990 to 1992 (standard tow=0.83 nautical miles), a 24-min tow at 2.5 knots in 1993 (standard tow=1.0 nautical mile), a 24-min tow at 3.0 knots since 1994 using the *URI* trawl (standard tow=1.2 nautical miles), and a 15-min tow at 3.0 knots using the *Campelen* trawl (standard tow=0.75 nautical miles).

The northern Gulf of St. Lawrence stratified random survey covers the St. Lawrence estuary and the northern Gulf, including around Anticosti Island and along the western Newfoundland coast. Based on the distribution of Witch Flounder in the area and the historical coverage of the survey, the analyses presented here follow the methods of Swain et al. (1998a), concentrated on strata 401-414, 801-824 and 827-832 (Figure 10). In some years, the survey did not sample all the strata (Table A1) which requires the estimation of witch flounder catch in missing years and strata. Because length frequency information was not available prior to 1987, the data from years 1984 to 1986 are not used in the analyses since they relied on length disaggregated information only. The combined 4RST indices therefore spans the years 1987 to 2016.

Southern Gulf of St. Lawrence RV Surveys

The southern Gulf of St. Lawrence stratified random survey has been conducted annually since 1971. The *E.E. Prince* using a *Yankee 36* trawl performed the survey from 1971 to 1984. The *Lady Hammond* using a *Western IIA* trawl took over in 1985 until 1991. The *Alfred Needler* using a *Western IIA* trawl became the survey platform starting in 1992 and ending in 2003. Since 2004, the *Teleost* has been conducting the survey with a *Western IIA* trawl (bottom panel of Figure A2). Comparative fishing experiments took place in 1985 between the *E.E. Prince* and the *Lady Hammond* (Figure A5), between the *Lady Hammond* and the *Alfred Needler* in 1992 (Figure A7) and between the *Alfred Needler* and the *Teleost* in 2004 and 2005 (Figure A9). In 2003, the usual sampling platform, the *Alfred Needler*, suffered a mechanical failure and its sister vessel, the *Wilfred Templeman* was used for that year's survey.

There are important diurnal differences in Witch Flounder catchability, the species tends to be more efficiently captured at night than during the day. The extent of this diurnal effect was estimated for the different vessels used in the southern Gulf surveys through the analysis of tows conducted at repeat locations and/or comparison of stratum-level estimates of Witch Flounder catches during the day and at night. In 1988, the *Lady Hammond* conducted 67 paired tows (one day tow and one night tow) at the same locations to obtain information about diurnal differences in catchability (Figure A6). A similar diurnal comparative experiment was conducted in 1998, 1999 and 2000 to estimate the day/night differences in catchability for the *Alfred Needler* (Figure A8).

The strata used in the analysis of Witch Flounder from the southern Gulf of St. Lawrence survey are those sampled over the entire time-series (strata 415 to 439, Figure A9) and do not include the shallow water strata that were added to the surveyed area in 1984. Witch Flounder is a deep water species and only nine individuals were ever captured in the shallow water strata 401, 402 and 403, so omitting these strata from the analyses is inconsequential.

Summary of Conversion Factors for Witch Flounder

In order to compute a single index for Witch Flounder in the Gulf of St. Lawrence (NAFO Divisions 4RST), a reference vessel, gear and diurnal period must first be identified. Following the previous assessments, this reference is a night tow conducted by the *Lady Hammond* using a *Western IIA* trawl. Trawl survey data collected from other vessels, gears and diurnal periods must be converted to the reference case prior to the computation of the Gulf-wide population index (Table A3; Figure A10).

Vessel and Gear Differences in Witch Flounder Catchability

For fish larger than 23 cm, a conversion factor of 2.0 is used to match the catch data from the *Alfred Needler* using a *URI* trawl to a *Lady Hammond Western IIA* equivalent. For fish smaller than 23 cm, a length-dependent relationship is used for the conversion since the *URI* trawl captured small fish with a different efficiency. The 2004 switch to the *Teleost/Campelen* also requires a length-dependent conversion as the *Campelen*'s efficiency at catching Witch Flounder varied with length with the *URI* trawl (top panel of Figure A10).

For the southern Gulf, the 1985 comparative fishing between the *E.E. Prince* using a *Yankee 36* trawl and the *Lady Hammond* using a *Western IIA* trawl indicated that the fishing efficiency of both vessel/gear was the same for Witch Flounder. So a conversion factor of 1.0 was used to transform the catch data from the *E.E. Prince/Yankee 36* into equivalent *Lady Hammond/Western IIA* units. The 1992 comparative fishing indicated a higher fishing efficiency of the *Alfred Needler* over the *Lady Hammond* and a conversion factor of 0.66 is used to convert between the *Alfred Needler* and the *Lady Hammond*. The 2004 and 2005 comparative fishing experiments between the *Alfred Needler* and the *Teleost* did not detect differences in fishing efficiency between the two vessels, so a conversion of 1.0 is used to convert between the *Teleost* and the *Alfred Needler* (bottom panel of Figure A10).

Diurnal Differences in Witch Flounder Catchability

The diurnal differences used to convert day tow to night tow equivalents are described in Swain and Poirier (1998) and Swain and Morin (2006). The nighttime catchability of Witch Flounder by the *Lady Hammond* was estimated to be 2.1 times that of its daytime catchability. In the southern Gulf, the nighttime catchability of Witch Flounder by the *Alfred Needler* and the *Teleost* using a *Western IIA* trawl was estimated to be 3.2 times that of the daytime catchability. In the northern Gulf, the nighttime catchability of Witch Flounder by the *Alfred Needler* using a *URI* trawl and the *Teleost* using a *Campelen* trawl was estimated to be 1.6 times that of the daytime catchability (Table A3; Figure A10).

Missing year-stratum combinations

In order to obtain a yearly stratified random estimate of catch biomass, all strata in the survey area must be sampled with at least two representative trawl tows. For cases where certain strata are not sampled in some years, the missing information must be estimated in order to correctly compute the yearly stratified mean of catch biomass. Table A1 and Table A2 show the missing stratum-year for the August and September surveys, respectively. As described in Swain et al. (1998b), Swain and Poirier (2001) and Swain et al. (2012), missing stratum-year values can be estimated by (1) using the yearly mean for all sampled strata in that year, (2) using the overall mean for that stratum over all available years or (3) using the prediction from a statistical model that estimates strata and year effects.

Survey coverage has been complete in the northern Gulf survey since 2011 (Table A1) and in the southern Gulf survey since 2004 (Table A2) so the estimation of catch rates in missing stratum-year was not modified since the 2012 assessment (Swain et al. 2012).

Single Index for the whole Gulf of St. Lawrence

All of the above conversion factors and estimations of missing year-stratum combinations are used to compute the Gulf-wide index for Witch Flounder. The steps required to compute the single index are as follows:

1. Vessel, gear and diurnal conversion factors are applied to the tow-level catch-at-length data to generate catch data equivalent to a night tow from *Lady Hammond* using a *Western IIA* trawl.
2. The weight associated with each length is determined from a yearly weight-length relationship and the total catch biomass per tow is computed.
3. Missing stratum-year combinations are estimated.
4. The proportional area of each stratum is used in the computation of the yearly stratified random mean catch per tow (Table A4).

The resulting index for the NAFO 4RST Witch Flounder stock covers the period 1987 to 2016 and is one of the three indices used to fit the population model used in this assessment.

Appendix A References

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Appendix A Tables

Table A1a. Number of valid tows by stratum for all years and strata sampled in the northern Gulf of St. Lawrence August survey, 1984 to 1999. Shaded cells show stratum and year combinations with zero or one valid tow.

Stratum	NAFO Div.	Surface (km^2)	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
401	4T	545	3	5	2	2	3	3	6	4	4	4	3	3	3	3	3	3
402	4T	909	3	5	2	2	3	3	6	5	5	3	3	1	3	2	3	5
403	4T	1190	1	5	4	2	3	3	4	3	3	3	3	3	10	10	3	5
404	4T	792	3	5	2	2	3	3	6	3	3	3	3	3	3	3	3	3
405	4T	1478	2	5	3	2	3	3	6	3	3	3	3	3	3	2	4	4
406	4T	2579	3	5	3	4	6	5	5	3	3	3	3	3	5	5	3	5
407	4T	2336	4	5	5	3	5	5	10	3	3	3	3	3	3	3	2	3
408	4T	2734	4	5	5	5	5	5	7	5	5	3	2	3	3	2	5	5
409	4T	909	0	0	0	2	3	3	3	3	3	3	0	3	4	3	3	4
410	4T	1818	0	0	2	0	3	3	2	3	3	3	4	6	10	6	5	4
411	4T	1859	0	0	0	2	3	0	3	3	3	3	4	7	9	7	6	9
412	4T	1283	0	0	0	2	3	0	3	3	3	3	4	5	3	3	3	4
413	4T	731	0	0	0	2	3	0	3	4	3	3	0	3	3	4	3	4
414	4T	388	0	0	0	2	3	0	3	2	3	3	1	3	3	3	3	4
801	4R	1214	3	4	2	2	3	3	6	3	3	4	3	3	3	3	4	5
802	4R	1369	4	5	3	2	3	3	6	3	3	3	3	3	3	3	3	3
803	4S	6976	4	6	10	12	13	10	23	3	2	4	3	3	3	3	4	5
804	4S	2490	3	5	5	3	4	4	5	4	3	3	4	3	3	3	3	3
805	4S	5762	4	5	7	10	12	8	14	7	4	4	6	4	11	8	4	5
806	4S	2127	3	4	3	5	4	3	4	4	3	3	3	3	3	3	3	3
807	4S	2370	3	5	4	4	4	4	3	12	11	10	5	5	4	4	3	3
808	4S	2428	4	6	5	4	4	3	8	7	6	4	5	4	3	3	2	4
809	4R	1547	3	5	3	2	3	3	6	9	7	6	4	3	3	3	3	3
810	4R	765	4	4	2	2	3	3	6	4	5	4	3	3	3	3	4	4
811	4R	1506	4	5	4	2	3	3	6	4	4	4	5	3	8	6	3	3
812	4R	4648	5	5	10	10	7	6	14	9	8	11	4	3	3	3	3	3
813	4R	3958	2	6	8	8	6	5	12	6	5	9	3	4	6	5	7	4
814	4S	1029	2	4	2	2	3	3	6	4	4	4	3	0	3	3	3	3
815	4S	4407	3	5	9	9	8	6	9	15	11	8	5	4	3	3	8	9
816	4S	5032	4	5	9	10	9	7	9	11	9	9	6	6	17	17	20	21
817	4S	3646	3	5	6	6	8	6	7	18	11	7	9	10	9	5	11	17
818	4S	2774	4	5	6	4	4	5	4	7	5	4	3	3	3	4	4	4
819	4S	1441	3	5	3	4	3	3	5	7	9	5	4	5	3	2	3	3
820	4R	1358	3	5	3	2	3	3	6	3	3	3	3	3	7	5	6	5
821	4R	1272	2	5	3	2	3	3	6	3	3	3	2	3	3	2	3	3
822	4R	3245	4	5	6	6	6	5	12	4	3	2	3	3	6	4	10	8
823	4R	556	2	5	2	2	3	3	6	3	3	3	2	3	2	3	1	3
824	4R	837	2	5	2	2	3	3	6	1	3	1	3	3	3	3	3	3
827	4S	3231	0	2	4	5	4	0	0	1	1	1	3	3	0	2	3	1
828	4S	2435	0	2	3	2	4	3	4	1	2	2	3	3	3	3	3	1
829	4S	2692	0	6	2	6	5	3	3	2	3	3	3	3	3	0	3	3
830	4S	1917	2	4	7	4	4	4	3	3	4	3	3	3	2	2	3	3
831	4S	1204	0	4	2	2	3	3	3	0	2	3	3	3	3	2	3	4
832	4S	3962	0	5	5	7	7	6	4	12	11	7	7	9	8	5	3	3
All	All	97749	103	182	168	173	198	160	273	217	198	180	152	160	199	171	185	204

Table A1b. Number of valid tows by stratum for all years and strata sampled in the northern Gulf of St. Lawrence August survey, 2000 to 2016. Shaded cells show stratum and year combinations with zero or one valid tow.

Stratum	NAFO Div.	Surface (km^2)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
401	4T	545	3	3	3	3	3	6	3	3	3	3	0	3	3	2	2	3	2
402	4T	909	3	3	3	2	0	3	3	3	3	3	3	3	3	3	2	3	2
403	4T	1190	3	3	3	3	6	4	3	3	3	3	3	3	3	2	2	3	2
404	4T	792	3	3	3	3	3	6	3	3	3	3	0	3	3	3	2	3	2
405	4T	1478	4	3	3	3	2	9	3	3	3	3	3	3	3	3	2	3	2
406	4T	2579	3	4	5	3	5	6	4	4	4	3	3	3	4	3	3	4	4
407	4T	2336	3	3	3	5	3	5	3	3	3	3	0	3	3	2	4	4	2
408	4T	2734	4	3	3	3	2	11	4	4	4	4	3	3	4	3	4	4	2
409	4T	909	4	4	3	3	3	4	3	3	3	3	3	3	2	3	2	2	2
410	4T	1818	4	4	5	3	3	6	3	3	3	3	3	3	3	3	3	3	3
411	4T	1859	5	9	4	3	5	8	3	3	3	3	3	3	3	3	3	2	3
412	4T	1283	4	4	3	3	2	5	3	3	3	3	3	3	3	3	2	2	2
413	4T	731	4	4	3	3	1	5	3	3	3	3	3	3	3	2	2	2	2
414	4T	388	4	4	3	3	3	6	3	3	2	1	3	3	2	3	2	2	2
801	4R	1214	5	5	2	3	3	4	3	3	3	3	2	3	3	3	3	3	2
802	4R	1369	3	3	2	8	3	8	2	3	3	3	0	3	3	3	3	3	2
803	4S	6976	3	4	6	2	1	14	6	8	8	7	3	6	7	3	10	8	5
804	4S	2490	3	6	3	2	3	10	3	3	3	3	3	3	3	3	4	4	4
805	4S	5762	5	5	12	8	4	10	8	7	7	6	4	5	7	5	7	7	9
806	4S	2127	3	3	3	3	5	4	3	3	2	3	3	3	3	3	3	3	3
807	4S	2370	4	3	2	1	0	7	3	3	3	3	3	2	3	3	4	4	4
808	4S	2428	3	3	3	3	0	3	3	3	3	3	2	3	3	2	4	4	4
809	4R	1547	3	3	3	3	1	5	3	3	3	3	3	3	2	3	3	3	4
810	4R	765	4	4	6	5	3	8	3	3	4	3	0	3	3	2	3	2	2
811	4R	1506	3	3	3	3	3	7	3	3	3	2	2	2	3	2	2	2	2
812	4R	4648	3	3	3	3	4	5	5	4	5	4	5	3	5	3	8	7	6
813	4R	3958	6	8	2	5	3	9	5	3	5	3	4	4	6	3	6	6	4
814	4S	1029	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2
815	4S	4407	9	2	6	3	3	14	5	5	6	5	5	3	6	4	6	7	6
816	4S	5032	21	1	6	4	4	11	7	7	7	6	4	4	3	6	6	8	7
817	4S	3646	13	14	8	5	2	7	5	5	4	5	3	3	4	4	5	4	6
818	4S	2774	4	5	7	5	1	6	4	4	2	4	3	4	3	3	4	5	4
819	4S	1441	4	1	1	3	0	8	2	3	3	2	3	3	3	3	2	2	2
820	4R	1358	5	3	2	3	3	14	3	3	3	3	0	2	3	3	3	3	2
821	4R	1272	3	3	3	3	3	7	3	3	3	3	2	4	3	3	3	2	2
822	4R	3245	10	9	3	3	3	8	4	4	4	3	4	2	4	2	5	3	4
823	4R	556	2	3	2	5	2	10	3	3	3	3	2	3	3	3	3	3	2
824	4R	837	2	3	2	2	3	6	3	3	3	3	2	3	3	2	2	2	1
827	4S	3231	3	0	2	2	3	6	4	4	3	3	3	2	3	2	2	3	3
828	4S	2435	0	1	0	3	3	1	3	3	3	3	3	2	2	2	2	2	2
829	4S	2692	2	0	2	1	0	8	4	4	3	2	3	2	2	3	2	4	3
830	4S	1917	3	2	1	1	0	6	3	3	3	3	3	3	2	3	2	4	4
831	4S	1204	3	3	1	3	3	4	3	3	3	3	3	3	3	2	2	2	2
832	4S	3962	3	3	2	3	4	8	4	5	5	3	4	3	6	4	4	4	3
All	All	97749	189	163	148	144	114	305	157	158	156	144	117	134	149	128	150	156	138

Table A2a. Number of valid tows by stratum for all years and strata sampled in the southern Gulf of St. Lawrence, 1971 to 1986. Shaded cells show stratum and year combinations with zero or one valid tow.

Stratum	NAFO Div.	Surface (km^2)	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
415	4T	2625	3	3	3	3	3	2	3	2	3	3	3	3	3	3	9	6
416	4T	3666	6	6	6	4	4	6	5	5	6	6	6	6	5	7	15	9
417	4T	1804	6	6	6	6	4	6	6	6	6	6	5	5	5	6	12	8
418	4T	1354	3	3	3	2	4	3	3	3	3	3	4	3	4	4	8	5
419	4T	1522	2	2	2	2	2	2	2	2	2	2	2	2	2	2	5	4
420	4T	2656	3	3	3	2	3	3	3	3	4	3	3	3	3	4	8	6
421	4T	1130	2	2	2	2	2	1	2	2	3	2	2	2	0	3	3	3
422	4T	4274	4	5	5	4	5	5	5	5	6	5	5	5	5	9	18	11
423	4T	11033	3	4	4	3	4	4	4	4	4	4	4	4	4	3	13	11
424	4T	3608	2	3	3	3	3	3	3	0	3	3	3	3	3	4	10	7
425	4T	2165	2	2	2	2	2	2	2	2	2	2	2	2	2	3	4	3
426	4T	1333	2	2	2	2	2	2	2	2	2	2	2	2	2	3	5	3
427	4T	3268	2	2	2	2	2	2	2	2	3	2	2	2	2	1	8	3
428	4T	694	2	2	2	2	2	2	1	0	2	2	2	2	2	1	5	3
429	4T	5827	4	3	3	3	3	3	3	3	3	3	3	3	3	6	11	7
431	4T	4876	3	3	3	3	3	1	2	3	3	3	3	2	3	4	7	7
432	4T	1034	2	2	2	2	2	2	2	2	2	2	2	2	2	6	8	12
433	4T	4082	2	3	3	3	3	3	2	3	3	3	3	3	3	11	15	25
434	4T	4161	2	3	3	3	3	3	3	3	3	3	3	3	3	5	12	8
435	4T	2196	2	2	3	2	2	2	2	2	2	2	2	1	2	4	7	5
436	4T	3292	2	2	2	2	2	2	2	2	2	2	2	2	2	5	8	6
437	4T	1701	3	3	3	3	3	3	3	3	3	3	3	3	3	4	8	7
438	4T	577	2	2	2	2	2	2	2	2	2	2	2	2	2	2	5	3
439	4T	1213	2	2	2	2	2	2	2	2	2	2	2	2	2	2	5	2
All	All	70091	66	70	71	64	67	66	66	63	74	70	70	67	67	102	209	164

Table A1b. Number of valid tows by stratum for all years and strata sampled in the southern Gulf of St. Lawrence, 1987 to 2002. Shaded cells show stratum and year combinations with zero or one valid tow.

Stratum	NAFO Div.	Surface (km^2)	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
415	4T	2625	6	8	6	5	7	11	5	5	5	7	7	6	6	6	5	6
416	4T	3666	9	13	7	8	9	13	9	8	8	9	8	8	8	8	7	9
417	4T	1804	7	10	6	4	5	15	5	4	5	5	5	5	4	4	4	4
418	4T	1354	6	10	6	3	4	6	4	3	4	4	5	4	3	4	3	4
419	4T	1522	4	6	6	3	4	4	3	3	4	4	4	4	3	4	3	4
420	4T	2656	6	5	5	5	7	11	7	6	7	9	12	6	6	6	5	6
421	4T	1130	3	0	3	2	3	4	4	3	4	3	5	3	3	4	3	3
422	4T	4274	11	10	11	9	10	27	12	10	12	12	14	11	10	10	7	11
423	4T	11033	17	6	19	20	22	43	25	22	22	23	26	22	22	22	14	22
424	4T	3608	6	4	7	7	9	18	10	8	8	9	8	8	8	8	8	8
425	4T	2165	3	6	4	3	5	12	5	4	5	6	5	5	5	5	4	5
426	4T	1333	3	6	4	3	3	7	4	3	3	5	4	3	3	3	2	4
427	4T	3268	5	2	8	6	7	7	8	7	7	8	7	7	7	7	6	7
428	4T	694	3	4	4	2	3	3	4	2	3	4	4	3	3	3	3	3
429	4T	5827	7	7	13	11	17	22	16	13	14	13	14	13	13	13	11	14
431	4T	4876	5	6	11	10	14	17	12	10	13	12	12	11	12	11	11	12
432	4T	1034	2	6	3	3	4	7	3	3	4	6	5	3	4	4	3	4
433	4T	4082	18	8	11	9	11	29	9	9	11	13	16	27	18	18	10	10
434	4T	4161	9	7	8	7	14	14	10	8	10	12	13	9	9	9	9	9
435	4T	2196	5	4	4	4	6	4	6	6	6	6	6	5	5	5	5	6
436	4T	3292	6	5	8	7	10	7	9	7	8	8	7	7	7	7	7	9
437	4T	1701	5	6	5	4	6	4	4	5	4	6	6	11	10	10	4	6
438	4T	577	3	4	3	3	4	3	4	3	4	5	5	3	3	3	3	3
439	4T	1213	3	4	4	3	4	3	5	4	4	5	4	8	8	8	4	4
All	All	70091	152	147	166	141	188	291	183	156	175	194	202	192	180	182	141	173

Table A2c. Number of valid tows by stratum for all years and strata sampled in the southern Gulf of St. Lawrence, 2003 to 2016. Shaded cells show stratum and year combinations with zero or one valid tow.

Stratum	NAFO div.	Surface (km^2)	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
415	4T	2625	3	9	6	6	6	7	6	5	4	5	4	6	6	6
416	4T	3666	3	12	16	8	8	8	8	8	6	5	6	8	8	8
417	4T	1804	2	7	7	4	4	5	4	4	3	4	3	4	4	4
418	4T	1354	2	7	5	4	3	4	4	3	3	3	3	3	3	3
419	4T	1522	2	7	6	4	4	4	4	3	3	3	3	3	3	3
420	4T	2656	3	6	10	6	7	6	6	5	4	5	5	6	5	6
421	4T	1130	2	3	3	3	2	3	3	3	3	3	3	3	3	4
422	4T	4274	4	11	18	10	11	9	9	9	8	9	9	10	10	9
423	4T	11033	10	37	34	23	21	23	18	16	14	16	13	17	17	17
424	4T	3608	3	9	12	8	8	9	7	7	7	8	5	8	8	8
425	4T	2165	1	5	8	5	5	6	4	3	4	5	3	5	5	5
426	4T	1333	2	3	3	3	3	4	3	3	3	3	3	4	5	4
427	4T	3268	3	7	8	7	7	8	6	6	6	7	3	7	7	7
428	4T	694	2	2	4	3	3	3	3	3	3	3	3	3	3	3
429	4T	5827	7	14	16	12	13	13	11	11	9	12	10	13	13	11
431	4T	4876	6	15	11	10	11	11	9	8	9	9	9	11	11	9
432	4T	1034	2	8	4	4	4	4	4	4	3	3	3	3	3	3
433	4T	4082	7	16	13	10	10	11	9	6	7	8	9	9	9	8
434	4T	4161	7	10	15	10	10	10	7	9	7	8	9	9	9	9
435	4T	2196	3	5	4	5	5	6	4	4	4	5	2	5	6	5
436	4T	3292	1	7	7	7	6	8	6	7	6	7	3	7	8	7
437	4T	1701	3	5	10	6	5	6	5	4	4	5	5	5	6	6
438	4T	577	0	3	5	3	3	4	4	3	3	3	3	4	4	3
439	4T	1213	0	4	6	4	4	5	4	3	3	3	3	3	5	3
All	All	70091	78	212	231	165	163	177	148	137	126	142	122	156	161	151

Table A3. Conversion equations and factors used to develop the standardized index of Withc Flounder for the Gulf of St. Lawrence to Lady Hammond Western IIA Night equivalents for each of the research vessel surveys. Index numbers reference the sequence as shown in Figure A10.

a) August Northern Gulf of St. Lawrence Survey by DFO Quebec Region (see Figure A10)

Index number	Conversion	Equation / conversion factor	Reference
2	Vessel / gear conversion Alfred Needler URI Night to Lady Hammond Western IIA Night	applies to lengths > 23 cm $\beta_N = 0.6978;$ $exp(\beta_N) = \ 2.009327$	Table 2 in Swain et al. (1998a)
3	Vessel / gear length dependent conversion Alfred Needler URI Night to Lady Hammond Western IIA Night	applies to lengths <= 23 cm $N_l^t = N_l^s / e^{\beta l}$ $\beta l = 47.184 * exp(-0.3094l) - 0.3532$ for target vessel t and source vessel s	Appendix B
5	Vessel / gear length dependent conversion Teleost Campelen Night to Alfred Needler URI Night	$N_l^t = N_l^s e^{\alpha + \beta l}$ $\alpha = 1.4901844;\ \beta = 0.0163411$ for target vessel t and source vessel s	page 4 and 5 in Swain and Morin (2006)
a	Diurnal conversion Lady Hammond Western IIA Day to Lady Hammond Western IIA Night	2.1	page 7 in Swain and Poirier (1998)
a	Diurnal conversion Alfred Needler Western IIA Day to Alfred Needler Western IIA Night	1.6	page 7 in Swain and Poirier (1998)
b	Diurnal conversion Teleost Campelen Day to Teleost Campelen Night	1.6	Swain and Morin (2006).

b) September Southern Gulf of St. Lawrence Survey by DFO Gulf Region (see Figure A10)

Index number	Conversion	Equation / conversion factor	Reference
1	Vessel / gear conversion E.E. Prince Yankee 36 Day to Lady Hammond Western IIA Day	1.0	Nielsen (1994),
4	Vessel / gear conversion Alfred Needler Western IIA Night to Lady Hammond Western IIA Night	$\beta_N = 0.4109$ $1/exp(\beta_N) = 0.663$	Table 1 in Swain et al. (1998a)
6	Vessel / gear conversion Teleost Western IIA Night to Alfred Needler Western IIA Night	1.0	Benoît (2006)
a	Diurnal conversion Lady Hammond Western IIA Day to Lady Hammond Western IIA Night	2.1	page 7 in Swain and Poirier (1998)
a	Diurnal conversion Alfred Needler Western IIA Day to Alfred Needler Western IIA Night	3.2	page 7 in Swain and Poirier (1998)
b	Diurnal conversion Teleost Western IIA Day to Teleost Western IIA Night	3.2	Swain and Morin (2006).

Table A4a. Stratum weights for the northern Gulf of St. Lawrence DFO Quebec Region survey used for the computation of the NAFO 4RST combined index. Shading identifies strata that overlap between the two surveys and the area of each stratum is divided by two.

Stratum	Area (km^2)	Proportional area / Weight
401	545 / 2	0.0015
402	909 / 2	0.0024
403	1190 / 2	0.0032
404	792 / 2	0.0021
405	1478 / 2	0.0039
406	2579 / 2	0.0069
407	2336	0.0125
408	2734	0.0146
409	909	0.0048
410	1818	0.0097
411	1859	0.0099
412	1283	0.0068
413	731	0.0039
414	388	0.0021
801	1214	0.0065
802	1369	0.0073
803	6976	0.0372
804	2490	0.0133
805	5762	0.0307
806	2127	0.0113
807	2370	0.0126
808	2428	0.0129
809	1547	0.0082
810	765	0.0041
811	1506	0.0080
812	4648	0.0248
813	3958	0.0211
814	1029	0.0055
815	4407	0.0235
816	5032	0.0268
817	3646	0.0194
818	2774	0.0148
819	1441	0.0077
820	1358	0.0072
821	1272	0.0068
822	3245	0.0173
823	556	0.0030
824	837	0.0045
827	3231	0.0172
828	2435	0.0130
829	2692	0.0144
830	1917	0.0102
831	1204	0.0064
832	3962	0.0211
Quebec proportion of total index weight		0.5011

Table A4b. Stratum weights for the southern Gulf of St. Lawrence DFO Gulf Region survey used for the computation of the NAFO 4RST combined index. Shading identifies strata that overalp between the two surveys and the area of each stratum is divided by two.

Stratum	Area (km^2)	Proportional area / Weight
415	2625 / 2	0.0098
416	3666	0.0273
417	1804	0.0134
418	1354	0.0101
419	1522	0.0113
420	2656	0.0197
421	1130	0.0084
422	4274	0.0318
423	11033	0.0820
424	3608	0.0268
425	2165 / 2	0.0080
426	1333	0.0099
427	3268	0.0243
428	694	0.0052
429	5827	0.0433
431	4876	0.0363
432	1034	0.0077
433	4082	0.0304
434	4161	0.0309
435	2196	0.0163
436	3292	0.0245
437	1701	0.0126
438	577	0.0043
439	1213 / 2	0.0045
Gulf proportion of total index weight		0.4988

Appendix A Figures

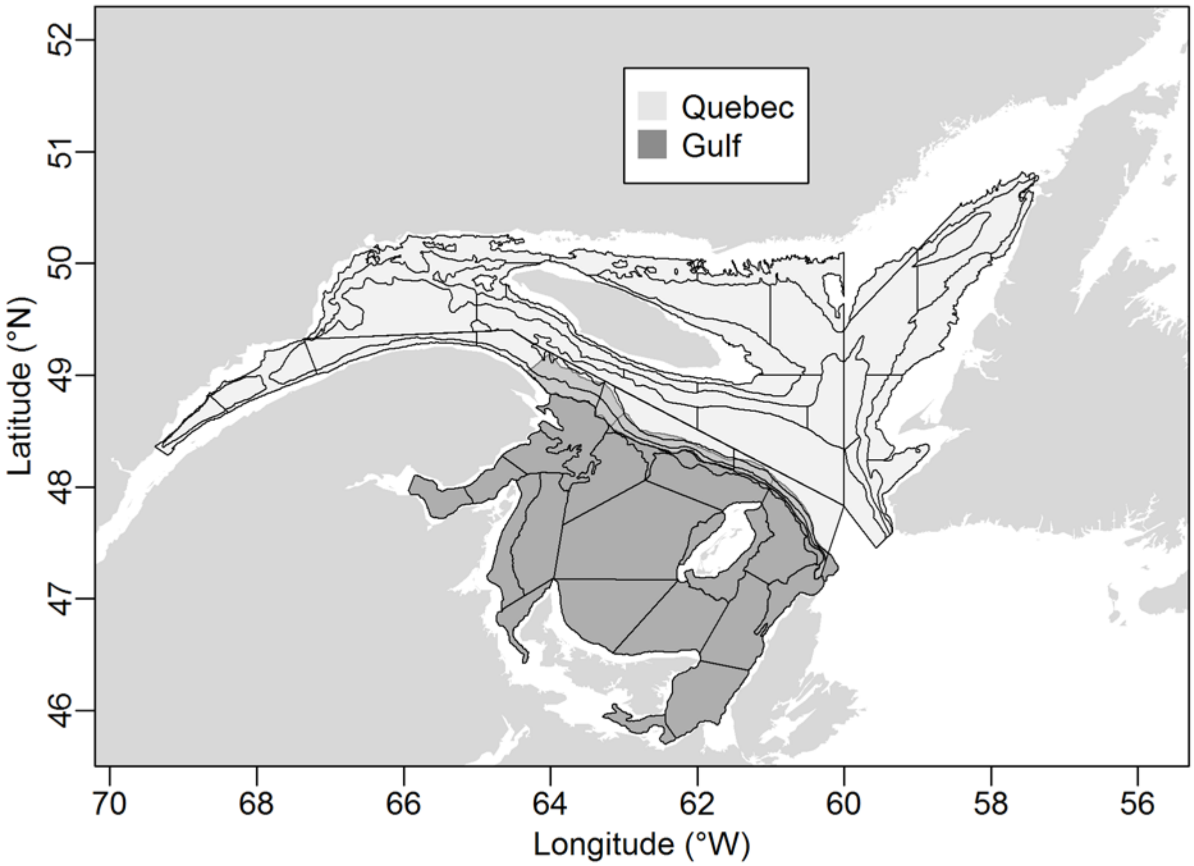

Figure A1. Strata boundaries for the Quebec Region's August bottom trawl survey of the northern Gulf of St. Lawrence and the Gulf Region's September bottom trawl survey of the southern Gulf of St. Lawrence, showing the overlapping strata located on the southern edge of the Laurentian channel.

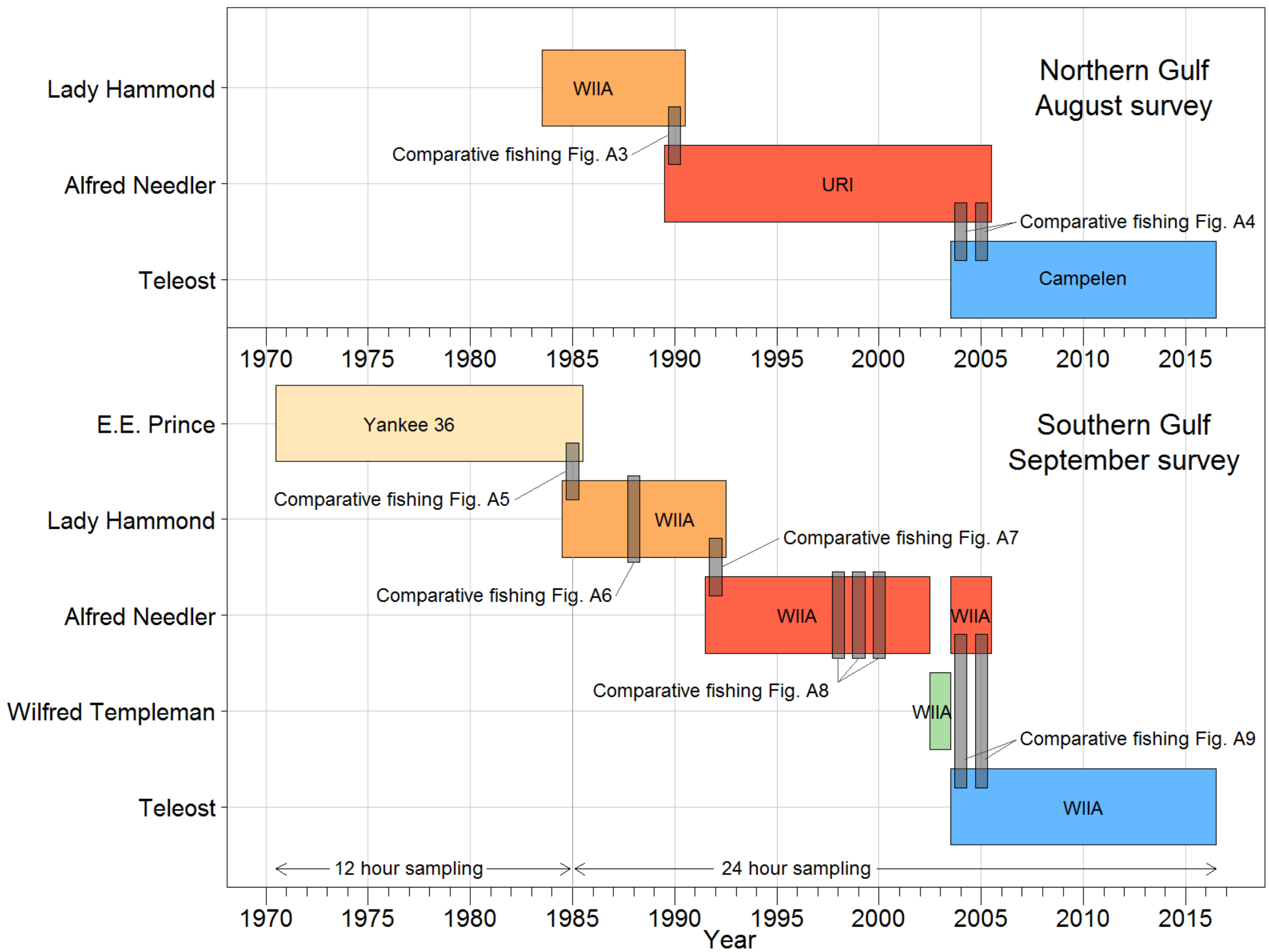

Figure A2. Timelines of the research vessel surveys in the Gulf of St. Lawrence showing vessels used and periods of comparative surveys.

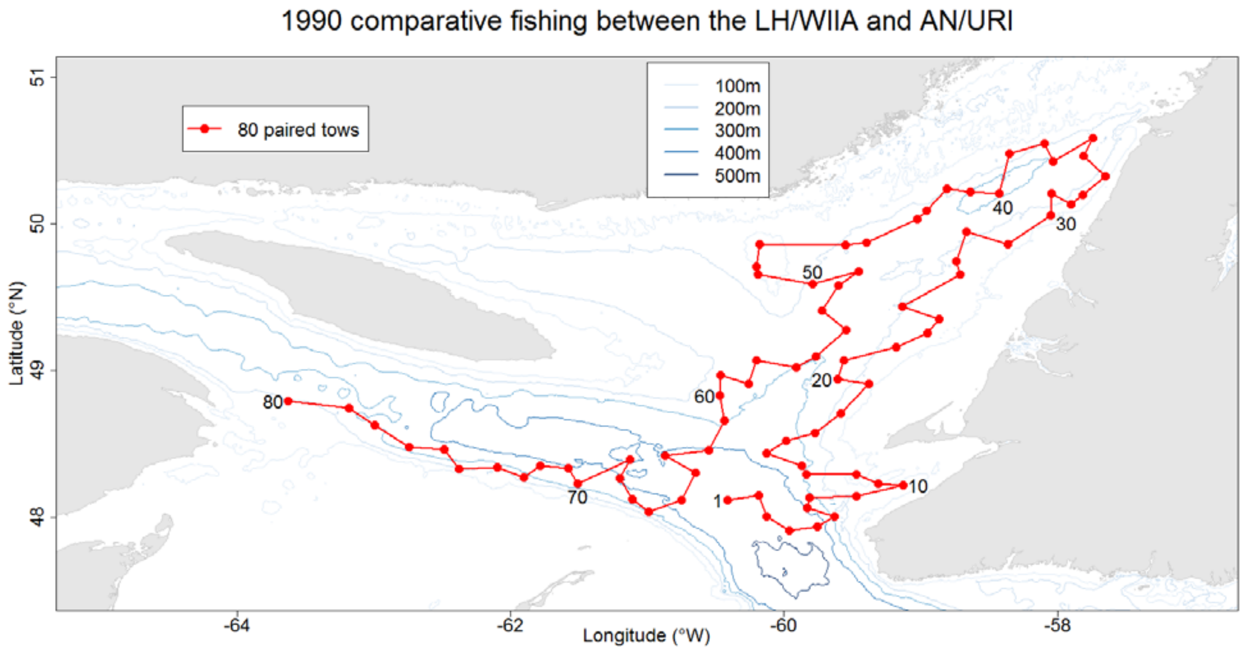

Figure A3. Location and sequence of the 80 comparative paired tows conducted in the northern Gulf of St. Lawrence during the 1990 comparative fishing experiment between the Lady Hammond using a Western IIA (LH/WIIA) and the Alfred Needler using a URI trawl (AN/URI). The analysis of fishing efficiency of the two survey platforms and the resulting conversion factors for Witch Flounder can be found in Swain et al.(1998a).

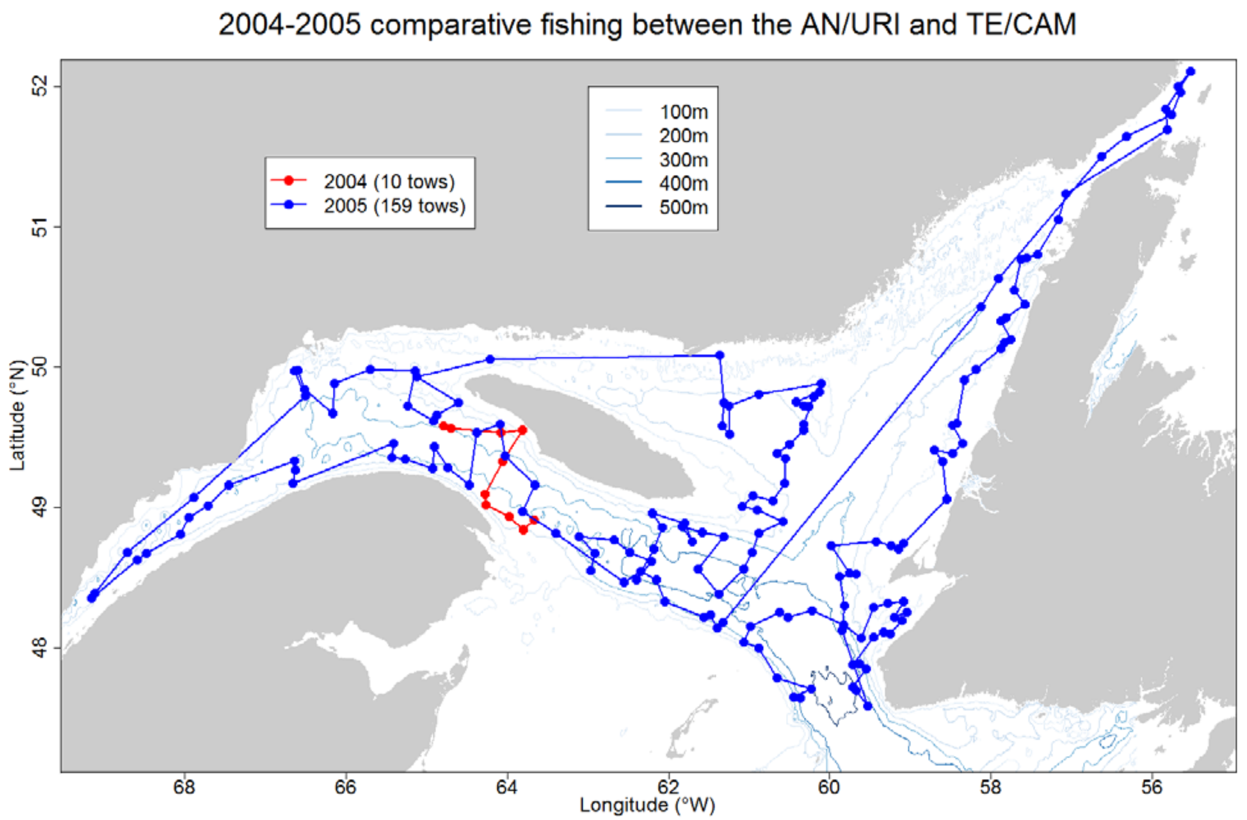

Figure A4. Location and sequence of the comparative paired tows conducted in the northern Gulf of St. Lawrence during the 2004 and 2005 comparative fishing experiments between the Alfred Needler using a URI trawl (AN/URI) and the Teleost using a Campelen trawl (TE/CAM).

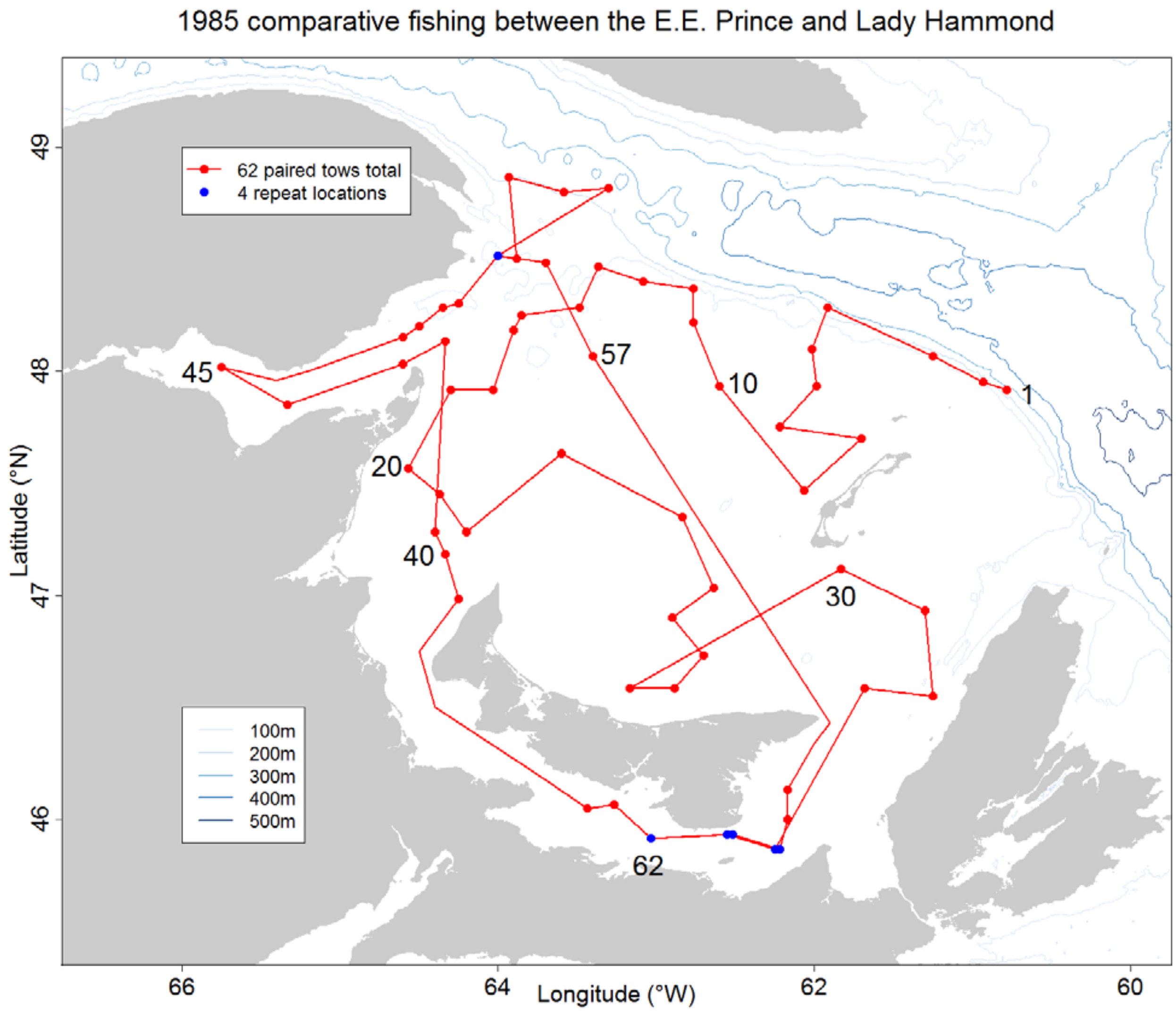

Figure A5. Location and sequence of the 62 comparative paired tows conducted in the southern Gulf of St. Lawrence during the 1985 comparative fishing experiment between the E.E. Prince using a Yankee 36 and the Lady Hammond using a Western IIA.

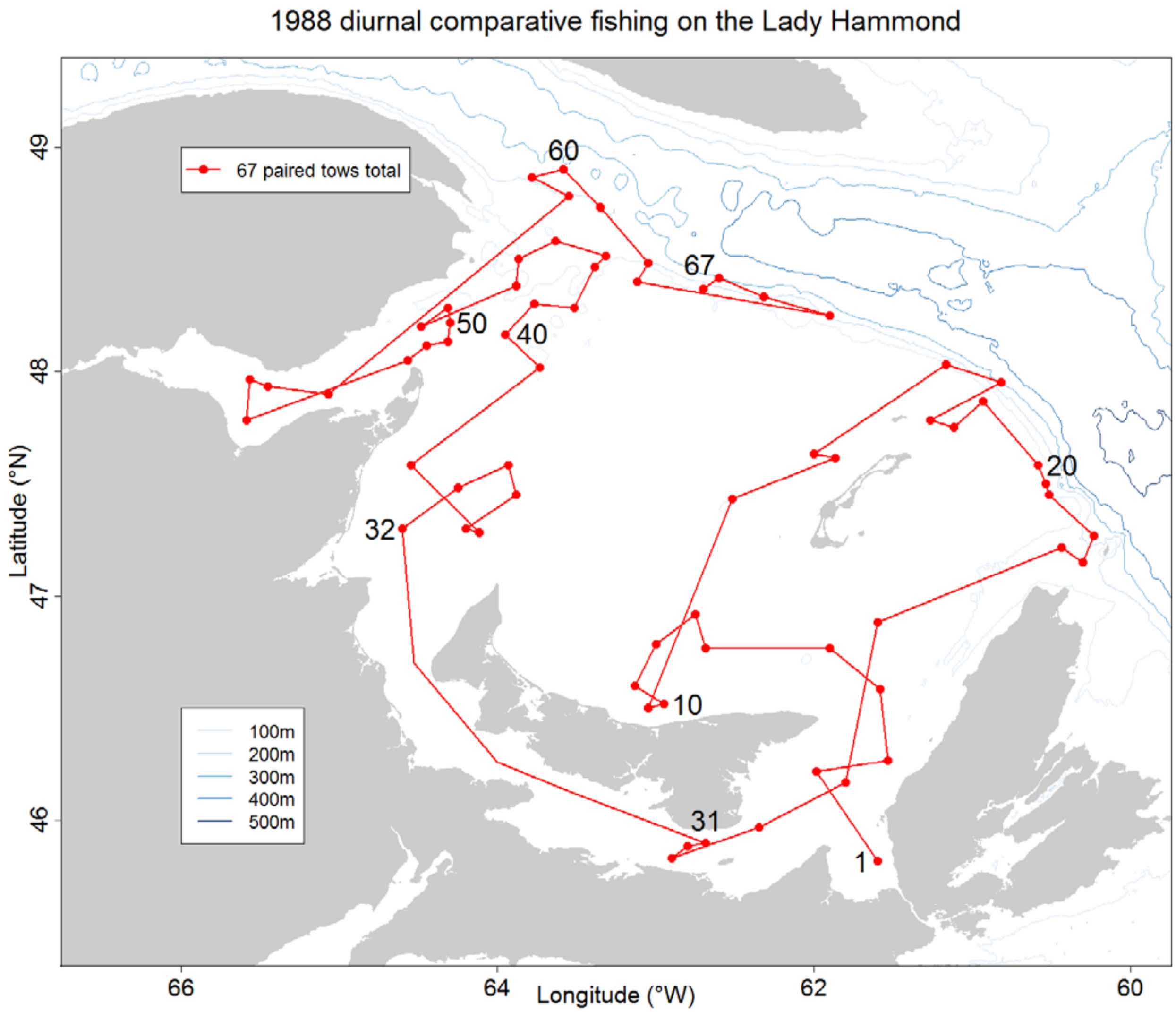

Figure A6. Location and sequence of the 67 diurnal comparative tows conducted by the Lady Hammond using a Yankee 36 in the southern Gulf of St. Lawrence during the 1988 comparative fishing experiments. Each tow location was sampled twice within a 24 hour period, once during the day (between 0700 and 1900) and once during the night (between 1900 and 0700).

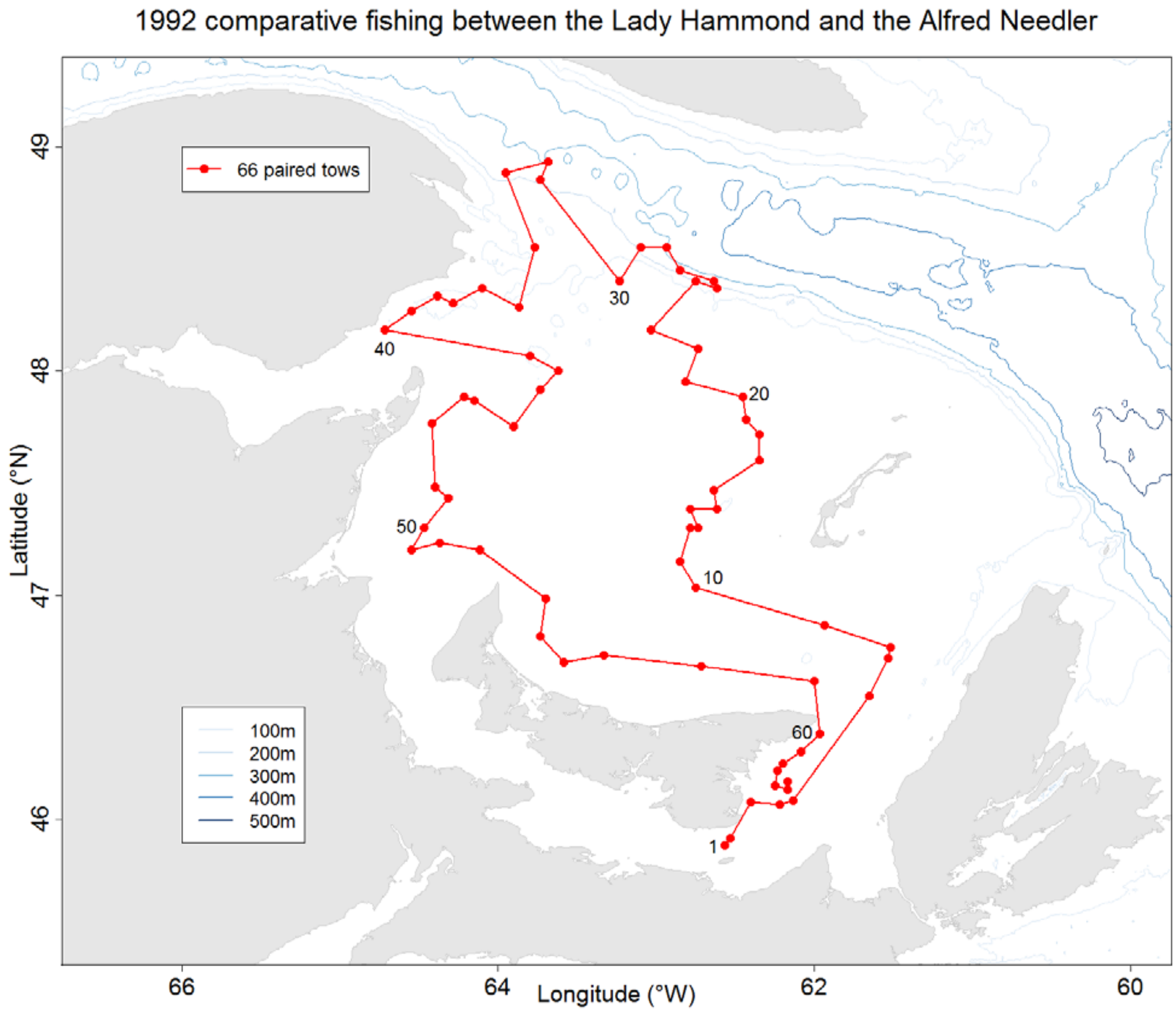

Figure A7. Location and sequence of the 66 comparative paired tows conducted by the Lady Hammond and the Alfred Needler during the 1992 comparative fishing experiments.

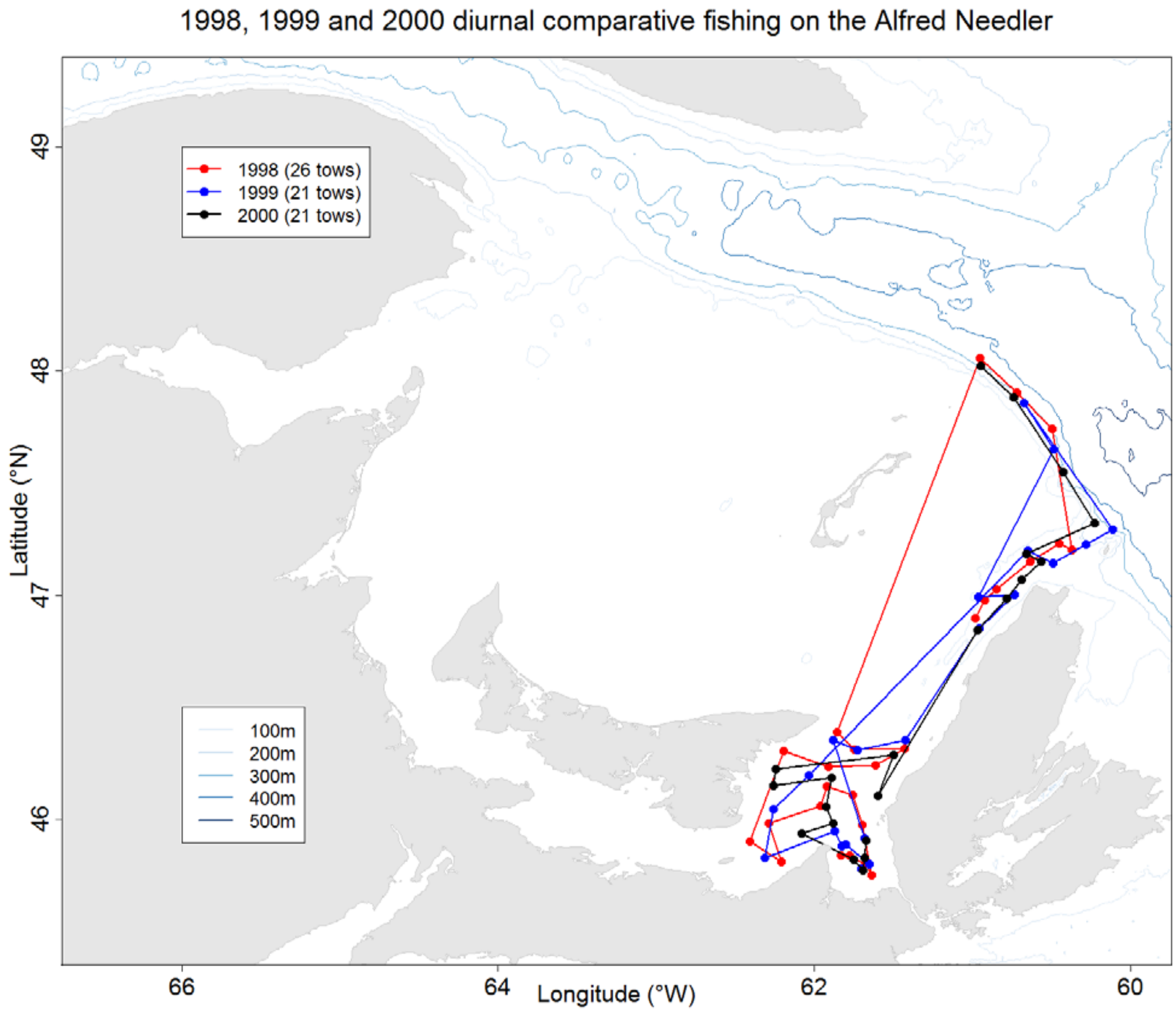

Figure A8. Location and sequence of the 68 diurnal comparative tows conducted by the Alfred Needler using a Western IIA trawl in the southern Gulf of St. Lawrence during the 1998, 1999 and 2000 comparative fishing experiments. Each tow location was sampled twice within a 24 hour period, once during the day (between 0700 and 1900) and once during the night (between 1900 and 0700).

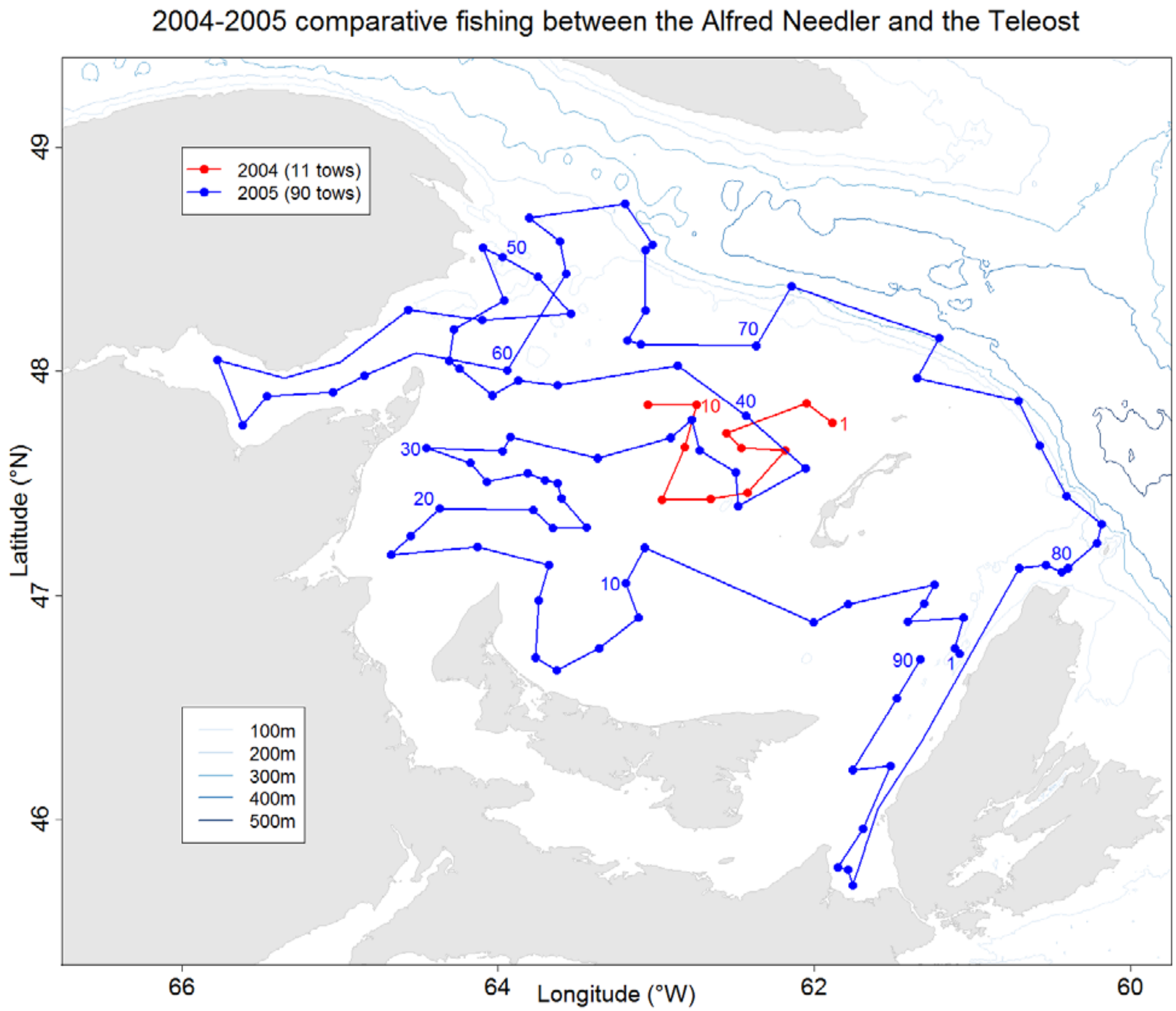

Figure A9. Location and sequence of the 101 comparative paired tows conducted by the Alfred Neelder and the Teleost during the 2004 and 2005 comparative fishing experiments.

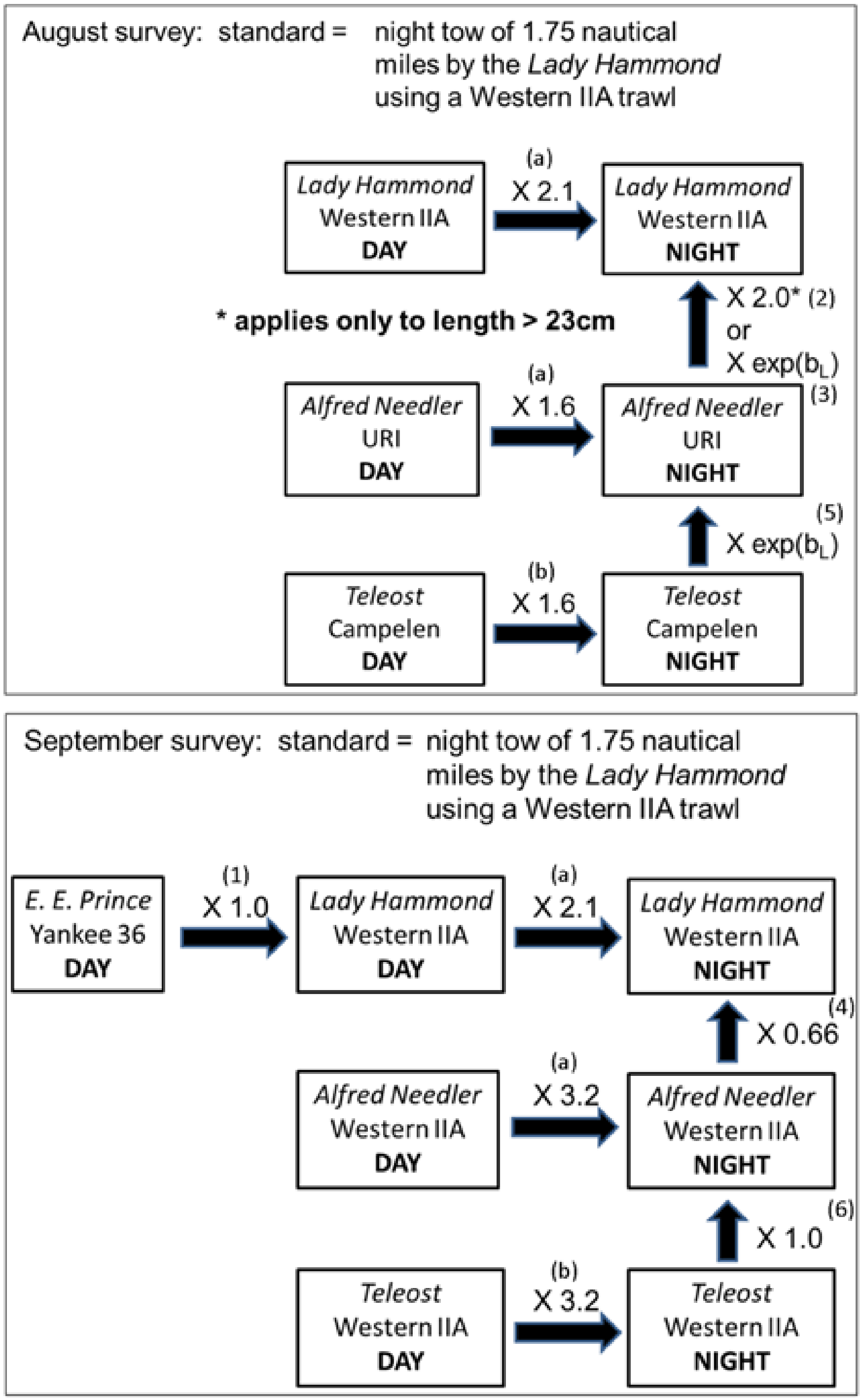

Figure A10. Summary of conversion factors between the different vessels and gears used during the August and September survey of the Gulf of St. Lawrence to derive the Gulf of St. Lawrence standard index for Witch Flounder. The conversion equations and references are summarized in Table A3.

APPENDIX B. LENGTH-DEPENDENT CORRECTIONS FOR DIFFERENCES IN FISHING EFFICIENCY FOR WITCH FLOUNDER (*GLYPTOCEPHALUS CYNOGLOSSUS* L.) BETWEEN THE WESTERN IIA AND URI TRAWLS IN SURVEYS OF THE NORTHERN GULF OF ST. LAWRENCE

Introduction

The relative abundance of groundfish in the northern Gulf of St. Lawrence has been monitored by bottom-trawl surveys conducted each August since 1984. Fishing in this survey was by the *Lady Hammond* using a Western IIA trawl from 1984 to 1989 and by the *Alfred Needler* using a URI trawl since 1990. A comparative fishing experiment was conducted in August 1990 to estimate relative fishing efficiency between these two vessels and gears. Swain et al. (1998) analyzed results of this experiment in order to estimate relative fishing efficiency for witch flounder (*Glyptocephalus cynoglossus* L.) between these two vessels and gears. They found that relative fishing efficiency between these two gears appeared to be strongly length-dependent, with relative efficiency greater for the URI trawl at small fish lengths and greater for the Western IIA at large fish lengths (Fig. 1). Swain et al. (1998) estimated relative fishing efficiency for witch flounder 24 cm or greater in length, since relative efficiency did not appear to vary at lengths over 24 cm. However, estimates of relative fishing efficiency at smaller lengths are needed to examine variation in relative abundance and distribution over the full size range of witch flounder. The purpose of this report is to estimate length-dependent calibration factors between the Western IIA and URI trawls.

Methods

Paired fishing between the *Lady Hammond* using a Western IIA trawl and the *Alfred Needler* using a URI trawl was conducted in the northern Gulf of St. Lawrence in August 1990. There were 94 successful tow pairs, conducted at 88 locations (i.e., there were 6 tow pairs conducted at sites previously fished in the experiment). Starting with the ninth tow, the 650 kg Morgère trawl doors initially used with the URI trawl were replaced by 950 kg Portuguese doors. The Portuguese doors have been used with the URI trawl on subsequent surveys (Diane Archambault, pers. comm.). Thus, this analysis was restricted to the 86 tow pairs using the Portuguese doors on the *Alfred Needler*. The target fishing procedure by the *Lady Hammond* was a 30-min tow at 3.5 knots. That by the *Alfred Needler* was a 20-min tow at 2.5 knots. Catches by both vessels were adjusted to a standard tow distance of 1.75 nautical miles.

Diurnal variation in catchability appears to differ between the two vessel/gear combinations. Night catchability is about 2.1 times day catchability for the *Lady Hammond*/Western IIA and 1.6 times day catchability for the *Alfred Needler*/URI (Swain and Poirier 1998). Before estimating relative fishing efficiency between the two trawls, all catches were adjusted to either night catchability (by multiplying day catches by 2.1 or 1.6) or to day catchability (by dividing night catches by 2.1 or 1.6).

Fishing efficiency of the *Alfred Needler*/URI trawl relative to the *Lady Hammond*/ Western IIA trawl was estimated for each 2-cm length interval from 8-9 cm to 46-47 cm and for fish 48 cm and greater using generalized linear models (McCullagh and Nelder 1989). A Poisson error distribution was assumed, because this distribution is often appropriate for counts data, including counts of organisms in sampling units (Pielou 1977). For the Poisson distribution, the natural link between the response variable and its predictors is the log. A log link has the advantage of ensuring positive predicted values and although this link does not permit predicted values of zero, predicted values may be infinitesimal and thus effectively zero. The model was of the form:

$$E[Y_{ij}] = \mu_{ij} = exp(\mu_0 + \alpha_i + \beta_j) \quad (1)$$

$$Var[Y_{ij}] = \emptyset\mu_{ij} \quad (2)$$

where Y_{ij} is the number of Witch Flounder caught in tow pair *i* by vessel *j* (the subscipt W is used for the *Lady Hammond*/Western IIA combination of vessel and gear and U for the *Alfred Needler*/URI combination), and ϕ is a parameter for extra-Poisson variation. Extra-Poisson variation ($\phi > 1$) was expected because organisms typically show a contagious rather than a random spatial pattern (Pielou 1977). The scale parameter ϕ was estimated using Pearson's χ^2-statistic (McCullagh and Nelder 1989). β_W was set to 0 (exp(β_W) = 1) in the parameter estimation, so exp(β_U) gives an estimate of fishing power by the URI trawl relative to the Western IIA trawl. Models were fit using S-Plus (MathSoft 1999).

A smooth function of length was fit to the estimates of β_U for each 2 cm interval. Length was taken as the mid-point of each 2 cm interval or the average length of the fish caught for the last interval (52.2 cm or 52.1 cm after adjustment to night or day catchability, respectively). An exponential model was used:

$$\beta_x = \alpha_0 + \alpha_1 e^{-\alpha_2 x} \quad (3)$$

where x is fish length in cm. Parameters and their approximate standard errors were estimated with the SAS procedure NLIN (SAS Institute Inc. 1990).

Results and Discussion

At lengths less than 11 cm, fishing efficiency was much greater for the URI trawl than for the Western IIA (Figure B2). At lengths above 24 cm, efficiency was significantly greater for the Western IIA than for the URI. The exponential model for the relationship between β_U and length provided a good fit to the estimated length-specific β_U's (Figure B2; $F_{3,18} = 90.97$ for the data adjusted to night efficiency and 79.43 for data at day efficiency, $P < 0.0001$ in both cases). Parameter estimates for the exponential model are given in Table A1. Relative fishing efficiency (exp(β_U)) is shown in Figure B3. At a length of 8.5 cm, the URI trawl is 20 to 25 times more efficient than the Western IIA, whereas at lengths over 24 cm the Western IIA is about 1.5 times as efficient as the URI trawl.

No Witch Flounder under 7.5 cm in length were caught by the Western IIA trawl during the comparative fishing experiment, and only three fish of these small sizes were caught by the URI trawl (6.3 after adjustment to a standard tow of 1.75 nautical miles). Thus, it was not possible to calculate correction factors for lengths under 7.5 cm, i.e., under the 7.5-9.5 cm interval. Comparative analyses will need to be restricted to lengths over 7.5 cm, or the correction factor for the 7.5-9.5 cm interval might be applied to smaller lengths. Analyses grouping all fish below 9.5 cm yielded correction factors similar to those obtained for the 7.5-9.5 cm interval:

Length interval (cm)	β_U	SE
A. night catchability		
7.5-9.5	3.022	0.458
5.5-9.5	3.094	0.471
B. day catchability		
7.5-9.5	3.296	0.518
5.5-9.5	3.368	0.533

After adjustment using equation 3 (using the parameter estimates in Table B1), catches by the URI trawl corresponded closely with those by the Western IIA (Figure B4). Adjusted and unadjusted length frequencies are compared in Figure B5 for the 1990-2000 surveys of the northern Gulf. Length frequencies for the 1987-1989 surveys, conducted by the *Lady Hammond* using a Western IIA trawl, are also shown for comparison. The relatively high catch rates of small Witch Flounder in 1990, 1991, 1997 and 1999 are not apparent after adjustment to equivalence with the Western IIA. On the other hand, catch rates at intermediate and large sizes are greater after adjustment.

Acknowledgements

I thank Diane Archambault for providing the data from the August surveys and for information on these data and on survey procedures.

Appendix B References

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Swain, D.P., Poirier, G.A., and Morin, R. 1998. Relative fishing efficiency for witch flounder of research vessels and gears used in bottom-trawl surveys of the Gulf of St. Lawrence. DFO Can. Sci. Advis. Secr. Res. Doc. 98/03.

Appendix B Tables

Table B1. Parameter estimates for equation 3 in the text, relating β_U to fish length ($\exp(\beta_U)$ is fishing efficiency by the URI trawl relative to the Western IIA trawl).

Parameter	estimate	SE
A. Night catchability		
$\alpha 0$	-0.3532	0.0725
$\alpha 1$	47.1840	21.4852
$\alpha 2$	0.3094	0.0497
B. Day catchability		
$\alpha 0$	-0.4414	0.0960
$\alpha 1$	25.1883	9.2587
$\alpha 2$	0.2270	0.0387

Appendix B Figures

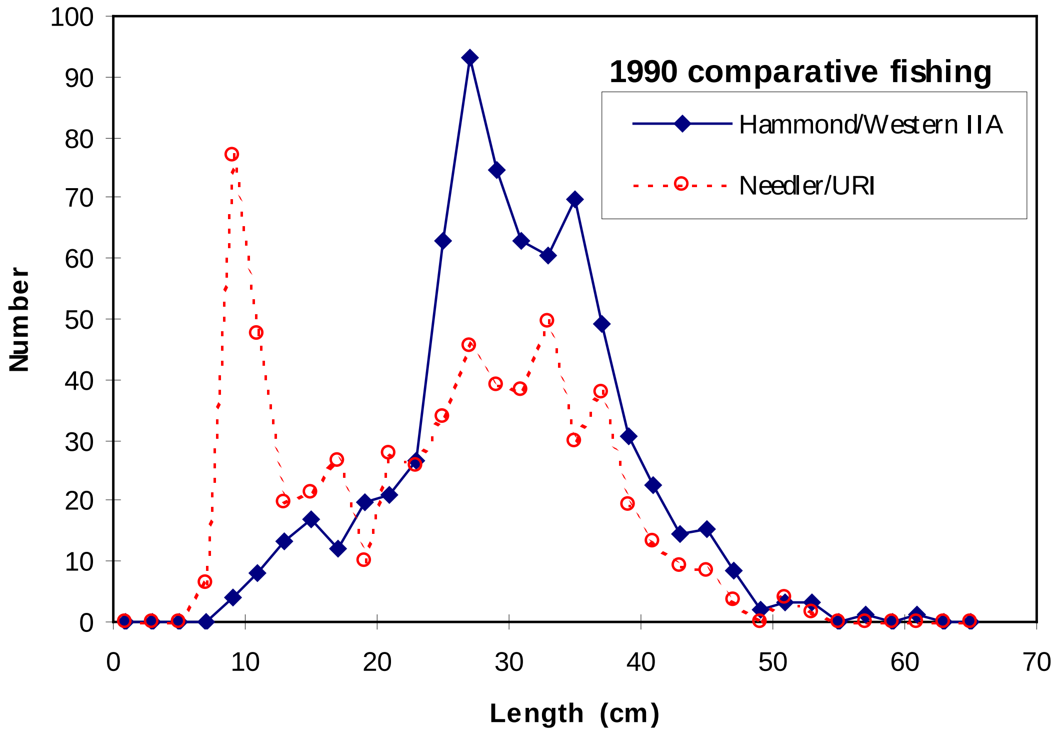

Figure B1. Number of Witch Flounder caught by length in paired tows in the northern Gulf of St. Lawrence in August 1990.

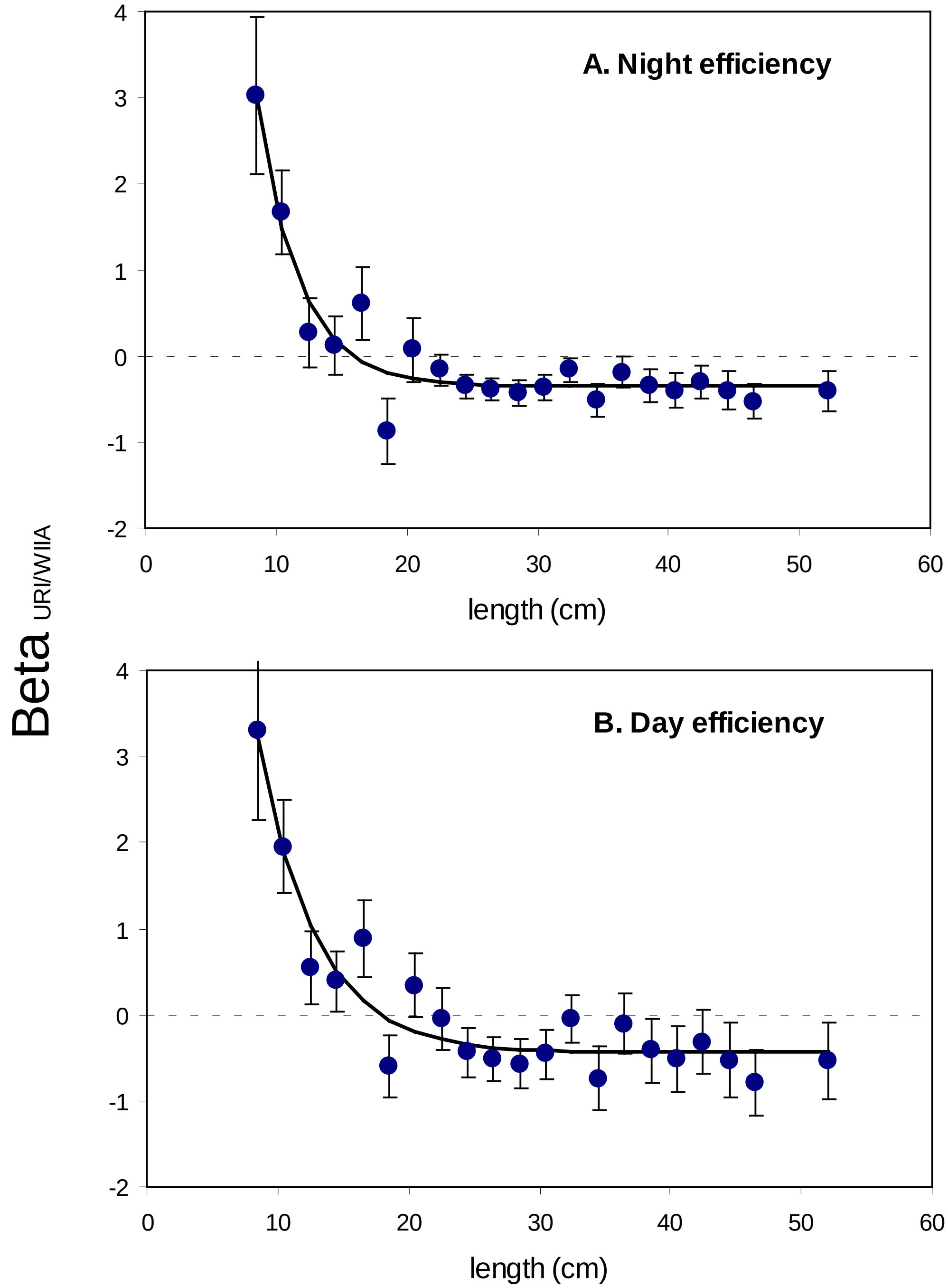

Figure B2. Length-specific differences in fishing efficiency for Witch Flounder between the URI and Western IIA trawls. Beta is the gear effect (URI relative to Western IIA) in generalized linear models assuming Poisson error (with overdisperion) and a log link between catch rates and the linear model with terms for site and gear. Models were fit for each 2-cm interval, with catch rates adjusted to night (A) or day (B) efficiency. Vertical lines show $\pm$2 SE. The curve is an exponential model fit to the length-specific estimates of β_U.

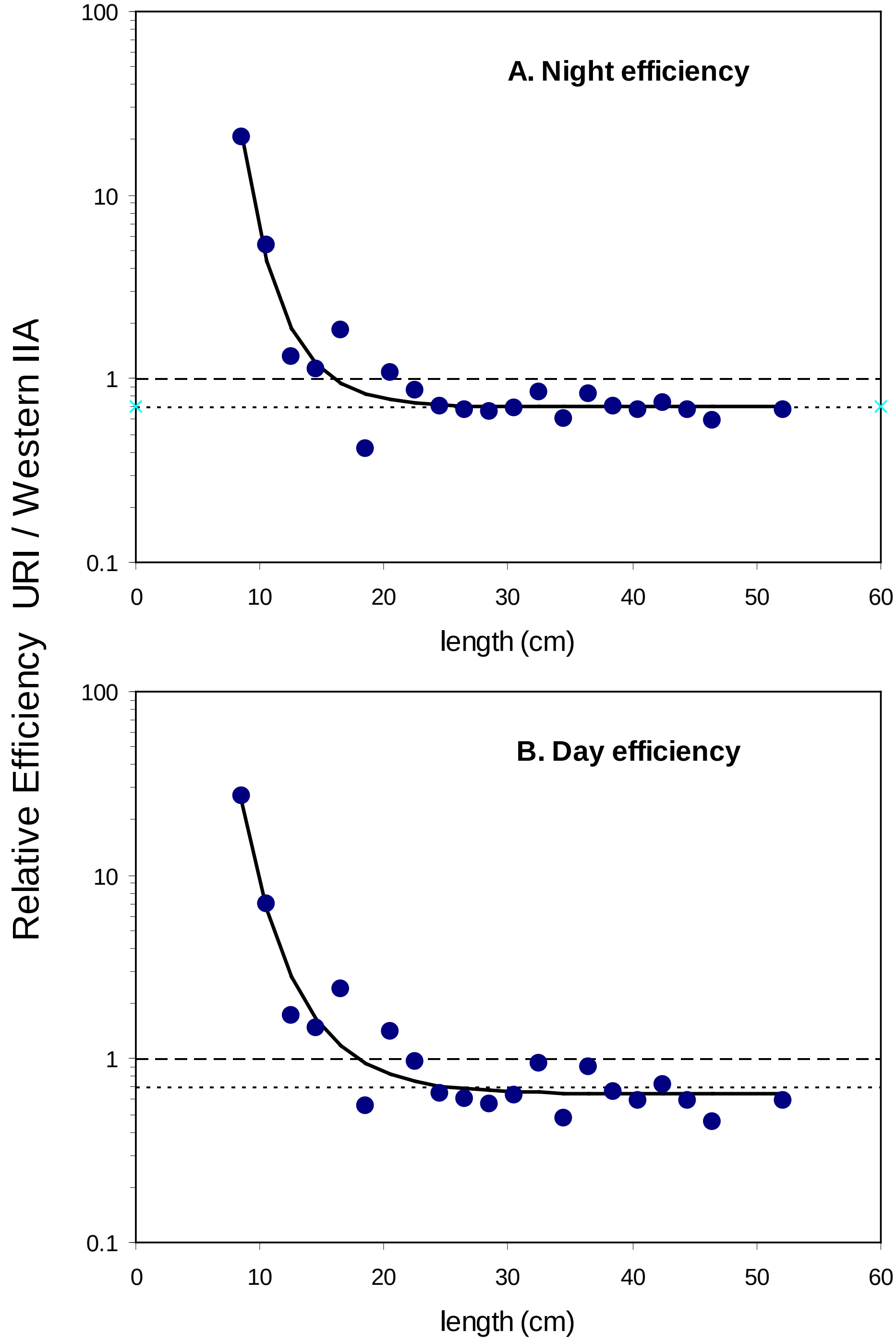

Figure B3. Length-specific fishing efficiency for Witch Flounder of the URI trawl relative to the Western IIA trawl. Circles show exp(β_U) from Figure B2 and the curve is the predicted relative efficiency from the exponential model shown in Figure B2 (given by the parameters in Table B1).

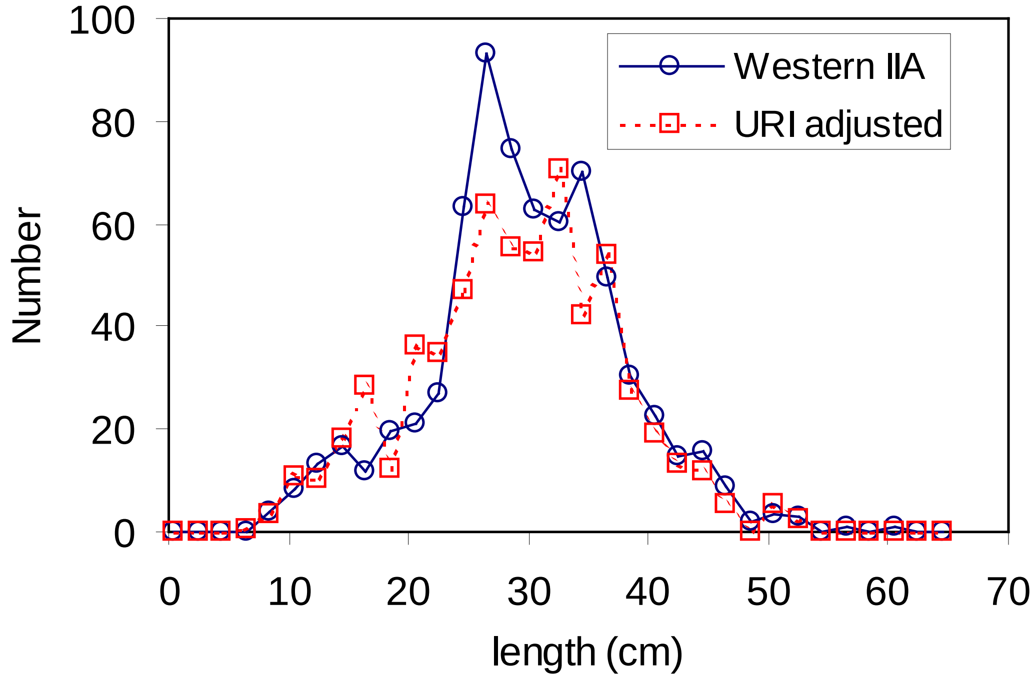

Figure B4. Comparison between Witch Flounder catches by the Western IIA trawl and those by the URI trawl adjusted using the exponential model shown in Figure B3A. Catches are the totals for 94 paired tows conducted in the northern Gulf of St. Lawrence in August 1990.

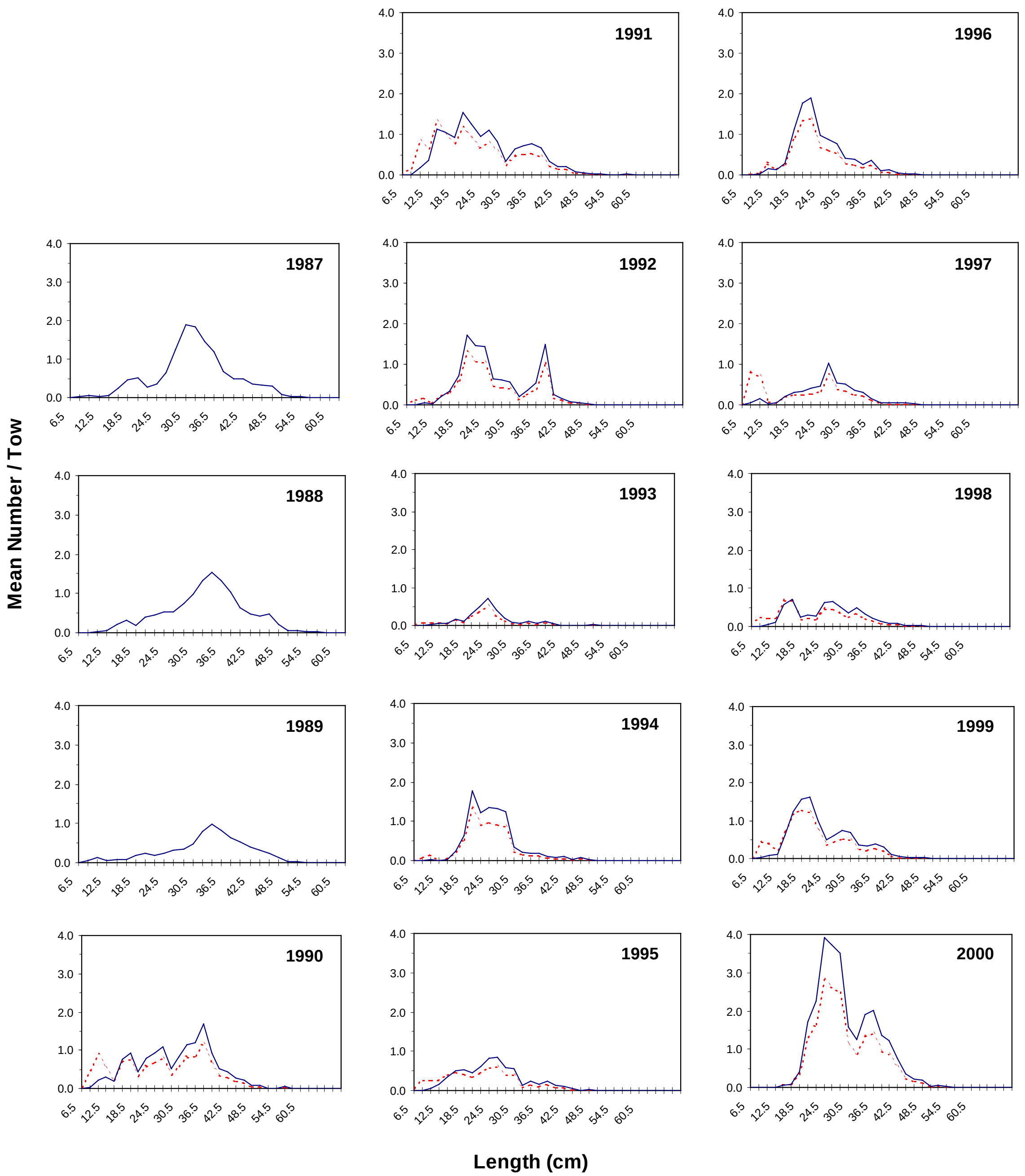

Figure B5. Stratified mean length frequencies of Witch Flounder caught in the August surveys of the northern Gulf of St. Lawrence. Catches are standardized to a night tow of 1.75 nautical miles. Surveys were conducted by the Lady Hammond using a Western IIA trawl (1987-1989) or the Alfred Needler using a URI trawl (1990-2000). Solid lines show catches adjusted to be equivalent to those by the Lady Hammond using a Western IIA trawl (1990-2000) and dashed lines show the unadjusted catches.