# The collapse and continued low productivity of a keystone forage

# fish species

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## Abstract

Capelin are a focal forage species of the Northwest Atlantic ecosystem as they act as an energy conduit from lower to higher trophic levels. Fisheries and Oceans Canada determined that the Newfoundland capelin stock (NAFO Divisions 2J3KL) suffered an order of magnitude decline in biomass in 1990-91. This collapse was concomitant with drastic changes observed in the ecosystem during the late 1980s and early 1990s. However, while the results of more than a dozen studies have supported a capelin stock collapse, an alternative non-collapse hypothesis proposed that rather than collapsing in 1990-91, the capelin stock either (1) changed its migratory patterns while the timing of the spring acoustic survey remained constant, leading to a spatio-temporal mismatch between the survey and the stock, or (2) became less migratory and remained inshore year round, therefore being largely underestimated by the offshore acoustic surveys. We tested the collapse and non-collapse hypotheses using multiple independent datasets, which included both fishery-dependent (inshore commercial catch) and fishery-independent (spring and fall acoustic and fall bottom trawl surveys, capelin larval indices, aerial surveys, predator diet and behavior) data, and diverse statistical methods. The weight of evidence approach led us to reject the non-collapse hypothesis and conclude that the Newfoundland capelin stock did collapse in 1990-91 with minimal recovery over the subsequent 25 years.

Keywords: capelin, *Mallotus villosus*, acoustic survey, regime shift, Newfoundland

## Introduction

Forage fish play crucial roles in many ecosystems, transferring the bulk of the energy from lower trophic levels to high trophic level predators. Typically, forage fish are small shoaling species that are characterized by short life expectancy and rapid, but variable, somatic growth driven by environmental factors. Forage fish species often exhibit ‘boom and bust’ population dynamics, i.e. their abundances change rapidly and substantially and undergo phases of extremely high or extremely low abundances (Schwartzlose et al. 1999, Chavez et al. 2003, Pikitch et al. 2012) . Each of these phases can last for prolonged periods. For example, the Norwegian spring-spawning Atlantic herring (*Clupea harengus*) stock collapsed in the late 1960s after a pulse of overfishing and remained at very low levels until the late 1980s (Toresen & Østvedt 2000, Dragesund et al. 2008, Skagseth et al. 2015); while sardine (*Sardinops sagax*) and anchovy (*Engraulis* spp.) have decade-scale regimes of high and low abundances where populations thrived for 20 to 30 years and then disappeared for similar periods (Schwartzlose et al. 1999, Chavez et al. 2003, Barange et al. 2009).

Capelin (*Mallotus villosus*) is the focal forage fish species in ecosystems of the North Atlantic Ocean (Templeman 1948, Vilhjálmsson 1994, Carscadden et al. 2001). The three largest and most economically valuable capelin stocks in the North Atlantic are in the Barents Sea, off the coast of Iceland, and along the Newfoundland and Labrador (Canada) continental shelf. The Barents Sea capelin stock experienced four collapses over the past four decades: the mid- to late-1980s, the mid-1990s, the mid-2000s, and the mid-2010s. The size of the stock fluctuated between 3 and 6 million tonnes (Mt) during the ‘boom’ phases and around 200 thousand tonnes during the ‘bust’ phases. There is general agreement that ecosystem changes, both bottom-up (i.e. temperature and North Atlantic Oscillation effects) and top-down forces, were behind these ‘boom-bust’ dynamics (Hjermann et al. 2004, Gjøsæter et al. 2009, Hjermann et al. 2010). The Icelandic capelin stock underwent similar dynamics, with three ‘bust’ phases over the past four decades: the early 1980s, the early 1990s, and most of the 2000s. The size of the stock was approximately 1.5-2 Mt during the ‘boom’ phases and between 100-500 thousand tonnes during the ‘bust’ phases (ICES 2017). The first two ‘bust’ phases were due to a combination of poor recruitment and the stock being easily available to the fishing fleet, while the most recent ‘bust’ phase was associated with poor recruitment attributed to an increase in the inflow of Atlantic water north of Iceland and a climate-related shift in distribution (Pálsson et al. 2012, Carscadden et al. 2013).

Fisheries and Oceans Canada (DFO) concluded that the NAFO (North Atlantic Fisheries Organization) Divisions 2J3KL capelin stock (hereafter Div. 2J3KL capelin stock) experienced an order of magnitude decline in 1990-91 with minimal recovery during the past two decades (DFO 1994, Miller 1997, DFO 2018). The size of the stock fluctuated between 2-6 Mt from 1982 and 1990, and between 25-900 thousand tonnes during the ensuing period (DFO 2018). The decline in capelin biomass was concomitant with drastic changes in the ecosystem during the late 1980s and early 1990s (deYoung & Rose 1993, Montevecchi & Myers 1997, Lilly et al. 2000, Rice 2002, Hammill et al. 2011, Pedersen et al. 2017) including major changes in the biology and ecology of capelin, such as delayed and protracted spawning, changes in their geographical and vertical distribution, and declines in somatic condition and size and age at maturity (Frank et al. 1996, Carscadden et al. 2001, Mowbray 2002, Nakashima & Wheeler 2002). The collapse and minimal recovery of capelin since 1990-91 is hypothesized to have been due to bottom-up processes that affected the recruitment and survival of capelin (Buren et al. 2014a, Obradovich et al. 2014, Murphy et al. 2018).

Frank et al. (2016) presented an alternative hypothesis that the Div. 2J3KL capelin stock did not collapse in the 1990s. The non-collapse hypothesis postulates that the offshore acoustic surveys have failed to detect large capelin aggregations since 1990 because of a spatio-temporal mismatch between the surveys and the stock. Specifically, the hypothesis states that post-1990 either (1) capelin changed their migratory patterns while the timing of the acoustic survey remained constant, leading to a spatio-temporal mismatch between the survey and the stock, or (2) capelin became non-migratory in 1990 and are therefore undetected by the offshore surveys. Support for the non-collapse hypothesis was based on changes in the biology of capelin post-1991 (e.g., distribution and demography), re-analysis of the offshore research surveys (multi-species bottom trawl and acoustic), and the response of various components of the ecosystem [e.g., zooplankton, Atlantic cod (*Gadus morhua*), seabirds, seals] to the large-scale changes that occurred in the region in the early 1990s. The objective of the current paper is to assess the empirical support for the capelin collapse hypothesis versus the non-collapse hypothesis using multiple, independent data sets and diverse statistical methods (e.g., triangulation, Munafò & Davey Smith 2018). The weight of evidence approach led us to reject the non-collapse hypothesis and conclude that the Newfoundland capelin stock did collapse in 1990-91 with minimal recovery over the subsequent 25+ years (Table 1).

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## Methods

To test the collapse and non-collapse hypotheses of the Div. 2J3KL capelin stock, we applied the weight of evidence approach. We organized our Results to address similar lines of evidence as Frank et al. (2016). In some Results sections, new data and analyses were presented to test alternative hypotheses. Each section concludes by summarizing support for each alternative hypothesis. Once this was completed for all sections, the weight of evidence approach was used to determine, overall, which hypothesis was best supported by the combination of previously-published results and additional analyses based on independent data sets (Table 1).

Here we succinctly describe methods for the new data analyses, *i.e.* analysis 1, analysis 2, etc.

*Capelin*

### *Offshore capelin abundance: acoustic surveys*

Awkward that it is under offshore section, but is starts describing inshore survey. Need to word it somehow

To test the non-collapse hypothesis, the acoustic biomass estimates from two inshore (Trinity Bay) acoustic surveys were analyzed. A seasonal acoustic survey (September and October 2003; January, June and September 2004-05) was conducted for on average 12 days (range 4 – 28 days) per sampling month from a 23 m inshore research vessel (CCGS Shamook) using a calibrated EK500 echo-sounder with a towed 38 kHz transducer. The acoustic survey followed a fixed transect design and covered both the main portion of Trinity Bay as well as the four arms (Fig. S1). The annual offshore spring (May) acoustic survey on the CCGS Teleost [equipped with either an EK500 (1999-2011) or an EK60 (2012-2017) echo-sounder] was extended inshore into Trinity Bay in 1999 (except for 2006, 2014-16). The inshore component of the May acoustic survey followed the same methods as the seasonal survey except the May survey only surveyed the main portion of the bay in 2 – 4 days (Fig. S2). When acoustic targets were encountered during a 24-hour period, sampling was conducted using bottom and midwater trawls to target the portion of the water column where the acoustic signal occurred. Length, sex and maturity stage were recorded for all capelin sampled, and ages were determined for two fish per sex per 0.5 cm interval. For methods to calculate capelin biomass from backscatter acoustic data see Mowbray (2002). If the capelin stock did not collapse, we would expect a large inshore resident capelin population composed of all age classes and spent/recovering fish inshore after summer spawning.

In years when the annual offshore May acoustic survey included an inshore component (1999-2005, 2007-13, 2017), we directly compared the capelin biomass inshore and offshore using a Pearson correlation. If the capelin stock did not collapse, we would expect a significant negative correlation between the inshore and offshore survey components (i.e. years with high capelin biomass inshore should have low biomass offshore).

We calculated the minimum inshore capelin biomass (kg km-2) that is required to compensate for the missing 3-6 Mt of capelin from the offshore surveys. Each year, approximately 71,000 km2 of the Newfoundland (NL) coast remains un-surveyed. The ‘back-of-the-envelope’ calculation is considered a minimum biomass estimate as we assumed a uniform capelin distribution throughout the inshore rather than attempt to estimate the patchy distribution of capelin inshore (i.e. aggregations). We compared the ‘back-of-the-envelope’ inshore biomass estimate to the biomass estimates obtained from the inshore surveys (2003-05).

### *Offshore capelin distribution: annual multi-species bottom-trawl surveys*

To test the hypothesis of a shoreward shift in capelin distribution post-1991, we revisited the center of gravity analysis (CG) of the fall bottom trawl survey (FBTS) data (e.g., DFO 2015 and Frank et al. 2016) by calculating the annual CG and inertia (*I*) for the years 1983-2016 (cf. Woillez et al. 2007). The CG metric was calculated by weighting the mean latitudes and longitudes of survey sets by abundance

where *xi* represents the coordinates of the sets, *zi* is abundance and *si* is the area of influence (Woillez et al. 2007). Given the irregular sampling of the FBTS, the CG indicator was weighted by area of influence, which was calculated using Voronoï tessellation of sets conducted within the survey strata each year (Woillez et al. 2009). The spatial dispersion of the population around its CG (i.e. inertia) was also calculated

and this spatial indicator was decomposed into two orthogonal axes describing the maximum and the minimum components of the inertia. Isotrophy (i.e. the shape of the dispersion around the center of gravity) was calculated by taking the square root of the ratio of the maximum and minimum components (Woillez et al. 2007). These calculations were conducted in R (R Core Team 2018) using the RGeostats package (Renard et al. 2018).

We included the pre- and post-1995 FBTS datasets in this analysis even though there is no conversion factor for the change in catchability of capelin from the Engel otter trawl (1978-1994) to the Campelen 1800 shrimp trawl (1995 onwards). Since the CG was calculated by year and its mean coordinate was weighted by abundance, the CG was relative within each year regardless of the probability of catching capelin (Fig. S3, S4).

### *Inshore recruitment index*

We re-examined the capelin larval productivity analysis by comparing late-larval densities in August in years pre-1991 to September in years post-1991 as the persistently late spawning of capelin since 1991 has delayed capelin larval emergence. This allowed us to compare productivity of similar larval developmental stages pre- and post-1991.

## Results

### *Capelin*

#### **Offshore capelin abundance: acoustic surveys**

From 1982 to 1992, Canada conducted fall (October) acoustic surveys for capelin in Divs. 2J3K (Fig. 1) (e.g., Miller and Carscadden 1984, Miller and Lilly 1991). The fall acoustic surveys targeted the maturing portion of the stock during winter feeding migrations to provide estimates of the size and number of maturing fish being recruited to the fishery the following year (Mowbray 2014). The capelin stock in Divs. 2J3K was also acoustically surveyed by the former USSR in November from 1982-1992 (Bakanev 1992; Fig. 1). The USSR fall acoustic surveys were conducted approximately a month later than the Canadian surveys and consistently estimated higher capelin abundances, which may have been due to timing, as capelin start aggregating into large overwintering shoals in November (Winters 1995). In 1990, the Canadian fall acoustic survey reported a very low capelin biomass (96 thousand tonnes, < 5% of the biomass surveyed in 1989) while the USSR acoustic survey reported the smallest biomass since 1984 (631 thousand tonnes) (Winters 1995) (Fig. 2). Both the USSR and Canadian acoustic surveys reported record low capelin biomass in the fall of 1991 and 1992 (16-55 thousand tonnes) (Winters 1995). A Canadian expanded fall survey (Divs. 2J3KL) in 1993-94 was conducted to determine if the ‘missing’ capelin could be located. However, the expanded fall acoustic survey confirmed the findings of the 1991-92 fall surveys that offshore capelin biomass was at record lows (Miller 1994, 1995).

Consistent with the fall acoustic surveys, both the Canadian (Div. 3L; 1983, 1985-93, 1996, 1999-2005, 2007-2015, 2017) and the USSR (Divs. 3LNO; 1975-1994) spring offshore acoustic surveys reported record low capelin biomass in 1991 (Bakanev 1992, Mowbray 2014) (Figs. 1, 2). The spring acoustic surveys encompassed an important capelin nursery area in Div. 3L and provided an annual index of capelin abundance recruiting into the fished population the following year (Mowbray 2014). In the Canadian spring acoustic survey, capelin biomass decreased two orders of magnitude from a high of 6 million tonnes in the late 1980s to 23,000 tonnes in 2010 (Mowbray 2014) (Fig. 2). While there has been an increase in capelin biomass in recent years (660-980 thousand tonnes in 2013-2015), capelin biomass overall has remained persistently low since 1990-91 (DFO 2018). Post-1991, capelin is only acoustically surveyed in the spring in Div. 3L by Canada with the discontinuation of the other three acoustic surveys in the early 1990s (Canada fall acoustic survey in 1994; USSR fall and spring acoustic surveys in 1992 and 1994, respectively).

While the offshore acoustic surveys provided strong evidence of a capelin collapse, they did not survey the inshore area. The non-collapse hypothesis uses observations of overwintering maturing capelin and large schools of immature capelin during winter surveys conducted in Trinity Bay in 1967-68 (Winters 1970) as evidence that significant densities of capelin can inhabit the inshore year round. The hypothesis of year round inshore residency of capelin was tested by conducting seasonal acoustic surveys in Trinity (2003-05) and expanding the annual offshore spring acoustic survey into Trinity Bay ([Fig. 1](#Ref514161259)). Seasonally, capelin densities were low in Trinity Bay in January and May, and the maximum mean density of capelin was observed in June (10,000 kg km-2), which corresponded with the start of the spawning period when capelin were highly aggregated inshore ([Fig. 3](#Ref514161259) a). In September and October, capelin densities were low once again (Fig. 3 a). There was also a distinct seasonal pattern in the age and maturity composition inshore. In January, overwintering fish were composed of ~70% immature age-1 and age-2 fish ([Fig. 3](#Ref514161271) b, c); the relative contribution of older fish increased through the spring as maturing age-2 and age-3 fish migrated into Trinity Bay ([Fig. 3](#Ref514161271) b, c); and by October, immature age-1 fish dominated the inshore area, strongly suggesting that spent mature fish either died or left the Bay (Fig. 3 b). In agreement with this finding, an inshore acoustic survey in January 2000 for overwintering cod from Conception Bay to Notre Dame Bay found concentrations of juvenile capelin (O'Driscoll & Rose 2001) but few older fish (G.A. Rose, unpublished data). These seasonal surveys found no evidence of a large inshore, non-migratory capelin stock.

We also tested the non-collapse hypothesis by investigating the spatial distribution of capelin in years when the annual offshore May acoustic survey included an inshore component (Fig. 2). Capelin biomass inshore and offshore in May was weakly negatively correlated but non-significant (Pearson Correlation: t = -0.83, df = 14, p = 0.42, R = -0.22). In the majority of years, > 90% of surveyed capelin biomass was offshore (Fig. 2). In four of the 14 years (2000, 2001, 2005, and 2010), 27 - 42% of the total capelin biomass surveyed was inshore (Fig. 2). A significant portion of the capelin population inshore in some years provides support for the non-collapse hypothesis. However, a simple ‘back-of-the-envelope’ calculation indicates that it is unrealistic to assume that the 3-6 Mt of capelin that are ‘missing’ in the offshore surveys since 1990 are now residing in the inshore. The minimum density for 3 to 6 Mt of capelin undetected in up to ~71,000 km2 of un-surveyed inshore waters would have to be between ~41,000 to ~170,000 kg km-2, uniformly distributed throughout the un-surveyed area. The maximum mean density of capelin observed in the Trinity Bay seasonal acoustic survey was 10,000 kg km-2 in June when capelin were highly aggregated inshore, and the maximum mean density of capelin inshore outside of the spawning period was only 120 kg km-2 (Fig. 3 a). Overall, these analyses indicate it is unlikely that the capelin stock became non-migratory and has remained inshore since 1990.

In summary, while the fall and spring acoustic surveys in Divs. 2J3KLNO support the collapse of the capelin stock, they cannot refute the hypothesis that capelin are non-migratory post-1990 as inshore areas were not systematically surveyed. However, the sheer number of fish required to compensate for the ‘missing’ 3-6 Mt of capelin offshore (~40,000 to 170,000 kg km-2) is staggering and was never detected by the inshore acoustic surveys. Inshore and offshore acoustic surveys in combination with the ‘back-of-the-envelope’ calculation provide strong support for the capelin collapse hypothesis (Table 1).

#### Offshore capelin distribution: annual multi-species bottom-trawl surveys

The westerly, inshore shift in the center of capelin concentration in 1996-2010 compared to 1985-1995 using the FBTS presence/absence data was considered support for the non-collapse hypothesis. However, the center of concentration of capelin from 1985-1995 was inshore in three high abundance years (1986-1988, Fig S2 in Frank et al. 2016). This variability may be related to the poor catchability of capelin in the Engel otter trawl, which was designed for harvesting commercial groundfish like flatfish and Atlantic cod. A CG analysis using only post-1995 FBTS data collected from the Campelen 1800 shrimp trawl showed a southerly shift in capelin distribution with a recent shift to the northwest in 2011-14 (DFO 2015). Neither of these analyses accounted for inter-annual changes in capelin spatial distribution due to sampling effort nor considered the spatial dispersion of the population around its center of gravity (i.e. inertia).

Center of gravity and inertia analyses based on Woillez et al. (2007) did not support the hypothesis that capelin shifted their distribution towards the inshore in 1990-91 and remained inshore for the subsequent three decades (Fig. 4). The FBTS survey coverage has been consistent over the past four decades so the effects of shifting survey coverage on the CG estimate was expected to be minimal (Fig. S2, S3). The CG trend in most decades was a pronounced shift in the north-south rather than the east-west axis (Fig. 4). There was, however, an inshore shift in the CG in the 2000s (Fig. 4). In the 2010s, the CG was offshore with shifts in the north-south axis, similar to the CG of the 1980s (Fig. 4). Like the acoustic surveys, the FBTS has poor survey coverage of the inshore. It is, therefore, possible that significant inshore aggregations of capelin could go undetected. However, if significant capelin aggregations were present inshore, then the CG would be oriented towards the inshore during years when more inshore strata were surveyed (1996-1998, 2000-2002, 2004-2006, 2010, 2013). Instead, the CG was oriented towards the inshore in the 2000s only (Fig. 4).

There has been a bias for increased catches of capelin in the FBTS post-1995 not only due to a change in sampling gear but also due to a change in habitat use of capelin (Mowbray 2002). Since 1991, capelin diel vertical migratory behavior changed with deeper distributions below the cold intermediate layer (~ 200 m) and in closer association with the bottom (peak density ~ 20 m off bottom) with capelin rarely found in the upper 50 m of the water column (Mowbray 2002). This change in behavior may be in response to a decline in the risk of groundfish (e.g., Atlantic cod) predation that may drive capelin into the pelagic zone (Rose 1993, McQuinn 2009). Due to the inherent biases in the FBTS data, we considered other data sources to investigate the center of distribution of capelin post-1991 (sensu Jech & McQuinn 2016). Juvenile capelin surveys using an International Young Gadoid Pelagic Trawl (IYGPT) in the northeastern bays and the offshore from 1994-99 found centers of distribution of capelin juveniles on the northern Grand Bank and along the northeast coast, but not in the bays, of Newfoundland (Anderson et al. 2002). This is consistent with capelin migrating to their nursery areas in the offshore. Thus, this independent study of juvenile capelin distribution supports our CG analysis using the FBTS data.

In summary, capelin distribution moved predominately in the north-south rather than east-west axis post-1991 based on a CG analysis that accounted for both inertia (i.e. spatial dispersion of the population around its center of gravity) and change in FBTS sampling effort. The CG analysis does not support the hypothesis of inshore residence of capelin since 1990-91, and, in combination with the finding that the center of juvenile capelin distribution was also offshore in the 1990s, supports the collapse hypothesis (Table 1).

#### **Residence time of capelin concentrations during offshore acoustic surveys in Div. 3L**

The non-collapse hypothesis assumes that the delay in the timing of capelin spawning post-1991 led to a mismatch in capelin availability to the spring acoustic survey, which has resulted in the spring acoustic survey severely underestimating capelin biomass offshore. Since 1991, capelin spawning has been persistently delayed on average by four weeks (DFO 2018). Meanwhile, the spring acoustic survey has been fixed spatially and temporally since the 1980s, which raises the possibility that the spring acoustic survey may not monitor migrating capelin consistently post-1991. However, it is important to note that the spring acoustic survey, which encompasses a capelin nursery area, was primarily designed to survey the non-migratory, immature portion of the stock, rather than the spawning migration (Mowbray 2014). All age classes acoustically surveyed are included in the annual index of capelin abundance, but the spring acoustic survey does not target capelin spawning migrations, and, therefore, should not be considered as a proxy for spawning stock biomass.

While a delay in the timing of spawning should not have a direct impact on the acoustic abundance index derived from the spring acoustic survey, earlier maturation could alter the age structure of the stock with inter-annual variability in the proportion of age-2s starting their adult migration patterns and may be unavailable to the survey. The proportion of mature age-2 capelin has increased since 1991 (4% pre-1991 compared to 37-79% post-1991) (Mowbray 2014, DFO 2018). In the Barents Sea, capelin growth may be stock abundance dependent, with faster immature (juvenile) growth observed when the stock size was small; and since timing of maturation is linked to growth, year classes with fast immature growth had earlier maturation (reviewed in Gjøsæter 1998). For NL capelin, growth of age-2 capelin was faster post-1991 (DFO 2018), which provides support for the collapse hypothesis (i.e. smaller stock size post-1991) and may explain the persistently earlier maturation of capelin since 1991. Despite the earlier observed maturation of capelin post-1991, there has been high internal consistency in the spring acoustic survey, with the index of abundance for the age-3 cohort being strongly correlated with the index of abundance for the age-2 cohort from the previous year (DFO 2018). This result implies that the spring acoustic survey can meaningfully capture relative changes in the overall stock, regardless of the proportion of migrating/non-migrating fractions.

If there was a significant inshore capelin population post-1991, we would expect to see this change in population demographics reflected in both the offshore acoustic survey and the inshore commercial catch. Prior to 1991, mature age-2 capelin were a negligible component of the inshore commercial fishery (< 5% of total catch) (Fig. 5). Post-1991, the contribution of mature age-2 capelin increased to almost half of commercial inshore catches (Fig. 5). However, the age structure of offshore catches are not consistent with the non-collapse hypothesis as the proportion of age-2 and age-3 fish sampled offshore has remained constant pre- to post-1991 at ~60% and ~28% of the catch, respectively (DFO 2018). Furthermore, the increased proportion of mature age-2 fish in the inshore catch post-1991 can be explained by the increase in proportion of age-2 fish maturing offshore and undergoing a spawning migration, rather than an absence of migration per se.

In summary, neither the persistent delay in spawning time nor earlier maturation of capelin post-1991 seem to significantly impact the ability of the spring acoustic survey to provide a relative index of capelin abundance. Data from the spring acoustic survey supports the capelin collapse hypothesis (Table 1).

#### Independent indices of inshore capelin abundance

Two inshore indices collected by DFO during the 1980s and 1990s were an aerial abundance index and inshore commercial catch rates. The non-collapse hypothesis implied that strong correlations between these two independent inshore indices post-1991 in addition to no obvious decrease in these indices between the late 1980s and the early 1990s was supportive of a stable stock. The aerial survey was designed to estimate capelin spawning stock biomass based on the area of capelin schools near spawning beaches in Div. 3L (Nakashima 1997). The aerial survey commenced in 1982, and initially followed four defined survey tracks in Conception and Trinity Bays during a fixed period of mid-June to early July (Carscadden et al. 1994). Protracted spawning post-1991 violated a key assumption of the aerial surveys: all spawning fish must arrive at the same time in each bay to form a single spawning peak. Protracted spawning from early July to mid-August in 1991-93 resulted in multimodal capelin spawning peaks that were covered with variable success by the aerial survey (Nakashima 1996). For example, in 1993, the peak spawning period was adequately surveyed in Conception Bay, but two spawning peaks in Trinity Bay, based on the egg deposition index, were missed (Nakashima 1996). In 1997, the geographical coverage of the aerial survey was reduced to two transects in the inner areas of Trinity and Conception Bays (Anon 1998). While the estimated aerial abundance index in 1997 was fourth highest in the series, there were concerns that the limited geographical coverage of the aerial survey did not accurately reflect the status of the stock (Anon 1998). Five of the eight years of aerial data post-1991 did not adequately cover peak spawning times (1991-93) and had reduced geographical coverage (1997-98). The aerial survey was discontinued in 1999 due to lack of funding.

Although considered an index of capelin spawning stock biomass during the 1980s, the inshore commercial catch rate data have not been included in the capelin stock assessment process since 1993 due to changes in management regulations post-1991. As a consequence of the small sizes of spawning capelin post-1991, management regulations introduced a size criterion of 50 capelin/kg to reduce dumping of undersized capelin (Carscadden & Nakashima 1997). This size criterion effectively closed the fishery in 1994 and 1995. From 1996, the size criterion was removed but management regulations to reduce discarding of small, unmarketable capelin resulted in fishing effort being concentrated to a few days when large capelin were available (Anon 1998). Post-1991, the inter-annual variability in participation in the fishery due to fish quality and market forces resulted in overall fishing effort being reduced and concentrated to when capelin were available resulting in high catch rates which rendered the inshore catch rate index useless as an indicator of stock abundance (Anon 1998).

In summary, due to changes in capelin biology and management measures post-1991, neither inshore indices provided reliable data on spawning stock biomass. Therefore, these indices should not be used to support or refute either hypothesis (Table 1).

#### Inshore recruitment index

Capelin larval production in August in Trinity Bay did not change appreciably pre- and post-1991, which was used as support for the non-collapse hypothesis. DFO collects two larval indices in Trinity Bay: an emergent larval index (3-10 mm SL) in a nearshore area and a late-larval index (10-30 mm SL) collected in the middle of the Bay (see Nakashima & Mowbray 2014 for more details). Given the persistently later capelin spawning since 1991, it is appropriate to compare late-larval densities in August in years pre-1991 to September in years post-1991 in order to compare productivity of similar larval developmental stages (Nakashima & Mowbray 2014). Late-larval densities in September during the 2000s were consistently lower and more variable than in August during the 1980s: average late-larval density in Trinity Bay in September 2002-15 was 30.9 m-2 (SD: 27.0, range 9.7 - 97.0 m-2) while in August 1982-86 was 48.8 m-2 (SD: 15.1, range 33.2-73.6 m-2) (Fig. 6). The substantial decrease in larval productivity post-1991 which is consistent with the capelin collapse hypothesis.

Post-1991, the emergent larval index (2001-2015) was related to the age-2 abundance index from the spring acoustic survey, which was lagged by 2 years in order to compare survival in the same cohort (Murphy et al. 2018). The positive, significant relationship between two fishery-independent inshore and offshore indices post-1991 supports previous research that identified early larval survival as an important driver of capelin recruitment (Frank & Leggett 1982, Leggett et al. 1984, Dalley et al. 2002). This result suggests that the offshore acoustic survey tracks inshore larval productivity, supporting the capelin collapse hypothesis. While it is possible that the offshore age-2 capelin abundance index reflects an overflow or spillover of age-2 capelin in proportion to inshore productivity, the inshore acoustic seasonal surveys did not find a significant inshore population of capelin outside of the spawning period.

In summary, comparing larval productivity in August pre-1991 and September post-1991 in combination with the significant relationship between two fishery-independent inshore and offshore indices post-1991 concurs with the collapse hypothesis (Table 1).

### *Ecosystem response*

#### Temporal dynamics of cod weight-at-age and condition

From the early 1980s to the late 1990s, the condition and weight-at-age of Atlantic cod in Divs. 2J3KL (also known as ‘Northern’ cod) declined markedly in the northern portion of its range (Div. 2J) with a similar declining trend in Div. 3K. Condition indices remained relatively unchanged in the southern portion of Atlantic cod’s range (Div. 3L). Weight-at-age of 4- and 5-year old Atlantic cod actually increased slightly in the mid-1990s in Div. 3L but later declined to the post-1991 average (Frank et al. 2016). This increase in weight-at-age in Div. 3L during the mid-1990s was considered support for the non-collapse hypothesis.

The increase in Atlantic cod weight-at-age and condition in Div. 3L in the mid-1990s may have been due to a shift in spatial distribution of both capelin and Atlantic cod. During and post-1991, capelin shifted its fall distribution from having two distinct aggregations, one in the northwest (Divs. 2J3K) and one in the southeast (Div. 3L, at the northern slope of the Grand Banks) to having only one in the southeast (Lilly & Davis 1993, Miller 1994), with records of excursions of capelin onto the Flemish Cap and the Scotian Shelf (Frank et al. 1996). Coincidently, Atlantic cod moved southward on the northeast Newfoundland Shelf in the late 1980s and early 1990s and aggregated within a small area on the northern Grand Banks and in the Bonavista Corridor (Rose 1993, Rose et al. 2000). Rose et al. (2000) hypothesized that the observed shift in Atlantic cod distribution was a response to the southerly distribution of capelin observed post-1991. Atlantic cod’s weight-at-age and liver condition worsened in northerly areas where there was no spatial overlap between Atlantic cod and capelin, and remained relatively stable in southerly areas where the collapsed Atlantic cod stock overlapped with capelin.

The existence of spatial structure in condition traits of Atlantic cod is not unique to the early 1990s and has been documented extensively in the scientific literature (e.g., Lilly et al. 2005, Neville et al. 2018, Rose & Rowe 2018), with historical latitudinal gradients in growth (length-at-age) and condition indices (liver, gutted and total body mass) (Buren et al. 2014b, Morgan et al. 2017). Atlantic cod weight-at-age and liver condition indices have never been spatially homogenous due to the species complex inhabiting distinct ecosystem production units in Divs. 2J3KLNO (e.g., Lilly 2005, Koen-Alonso et al. 2013, Morgan et al. 2017). These units are characterized by distinct marine communities and food web systems (Koen-Alonso et al. 2013, NAFO 2014, Pepin et al. 2014). Therefore, the non-homogenous traits of Atlantic cod from Labrador (Div. 2J) to the southern Grand Banks (Divs. 3NO) are typical of this stock complex and cannot be used to support the non-collapse hypothesis.

In summary, the lack of change in Atlantic cod condition in Div. 3L in the 1990s does not support the non-collapse hypothesis as Atlantic cod condition is associated with spatial overlap of capelin (Table 1). Atlantic cod condition was worse in Divs. 2J3K where capelin were no longer observed post-1991 compared to Atlantic cod in the south (Div. 3L) where the capelin population had contracted.

#### Harp seal population trends and diet

Large numbers of starving harp seals (*Pagophilus groenlandicus*) were observed following the collapse of capelin in the Barents Sea in the mid-1980s (Haug & Nilssen 1995). The absence of an obvious response in Northwest Atlantic harp seal populations to the proposed collapse of the capelin stock in 1991 was considered support for the non-collapse hypothesis. However, there are significant differences between the two regions, and populations of predators may be expected to respond differently in the two areas. In the Barents Sea, the collapse of capelin during the mid-1980s occurred when the stocks of other energy rich forage fish, including Atlantic herring and Arctic cod (*Boreogadus saida*), were severely depleted (Hamre 1994, Hop & Gjøsæter 2013). Therefore, the effects of the capelin collapse were amplified and reached several taxa including seals, seabirds and Atlantic cod (Hamre 1994). Barents Sea capelin declined in 1992-93 without a similar occurrence of starving seals which was likely due to the availability of alternative prey (Atlantic herring and polar cod, Nilssen et al. 1998). In the Northwest Atlantic, Arctic cod and Atlantic herring were available as prey to harp seals during the early 1990s (Lilly et al. 1994, Bourne et al. 2015, DFO 2017), as indicated by the large proportional increase of these alternate prey in harp seal diets during this period (Stenson 2012).

While Northwest Atlantic harp seals did not show catastrophic mortalities post-1991, they have been impacted by the decline in capelin. Until the late 1970s, pregnancy rates were consistently around 85%. Since then, pregnancy rates have been highly variable (ranging from ~20% to 75%) with an overall declining trend (Stenson et al. 2014, Stenson et al. 2016). In addition, late-term abortions have become a regular occurrence since the late 1980s (Stenson et al. 2016). Stenson et al. (2016) found that while the general decline in harp seal fecundity reflected density-dependent processes associated with increased population size, including the late-term abortion rates in their model allowed them to explain the large inter-annual variability in pregnancy rates. Changes in the abortion rates, in turn, were found to be influenced by ice cover in late January and capelin biomass. Buren et al. (2014a) showed that capelin abundance is associated with ice conditions, suggesting that late January ice conditions reflect changes in environmental conditions that influence many prey species. While higher catches in the Canadian commercial seal hunt from 1996-2008 contributed to reductions in the rate of harp seal population growth, lower pregnancy rates also had a major impact on the dynamics of this population. This is evident in the past decade where the commercial catches have declined but there has not been a concomitant increase in harp seal population abundance.

In summary, we cannot conclude that the absence of starving seals post-1991 indicates that capelin biomass remained stable and did not collapse (Table 1). However, a declining trend in pregnancy rates and an increase in late-term abortions, which were related to capelin abundance, suggest a change in capelin abundance has been a limiting factor in harp seals fecundity during the past three decades.

#### Seabird population trends and diets

Populations of common murres (*Uria aalge*), Atlantic puffins (*Fratercula arctica*) and northern gannets (*Morus bassanus*) off eastern Newfoundland increased in the 1990s (Chardine et al. 2003). Given that capelin is an important prey item for these predators, particularly during the breeding season, increases in their populations appear to be inconsistent with the collapse hypothesis.

Fish stocks in general and pelagic stocks in particular contract their geographic range during periods of rapid population decline (Winters & Wheeler 1985, Worm & Tittensor 2011, Burgess et al. 2017). This pattern has been described for several finfish and shellfish populations (Prince et al. 2008, Wilberg et al. 2009), including Atlantic cod (Rose & Kulka 1999) and Northwest Atlantic herring stocks (Winters & Wheeler 1985). Capelin’s center of distribution moved southward during the early 1990s, i.e. closer to the vicinity of seabird colonies along Newfoundland’s northeast coast. Throughout the 1990s, common murres on Funk Island almost exclusively fed capelin to their chicks during the breeding season (Davoren & Montevecchi 2003). Consistently high local abundances of capelin at annually persistent spawning sites within seabird foraging ranges allowed for the high percentage of capelin in parental deliveries (Davoren et al. 2012, Davoren 2013). Therefore, a higher proportion of capelin in common murre’s diet post-1991 is not inconsistent with the collapse hypothesis, whereby the range of the collapsed capelin stock overlapped with the foraging range of seabird breeding colonies.

Capelin also represented significant proportions of northern gannet’s diet from 1990-2012 (20 – 100 %) in contrast to pre-1990 (<12%, Montevecchi 2007, Bennett et al. 2013). This change in northern gannet diet was proposed as support for the non-collapse hypothesis. However, this change in diet occurred at the same time as the cold water intrusion of the early 1990s that was associated with a decline in the abundance of northern gannet’s preferred large pelagic prey (mackerel *Scomber scombrus*, Atlantic saury *Scomberesox saurus* and short-finned squid *Illex illecebrosus*) which are found in warm waters (Montevecchi & Myers 1997). For example, when mackerel and saury were more abundant in the region in 2005 and 2006 when waters were warmer, the percentage of capelin in the gannets’ prey landings fell to 13% and 2% (Montevecchi 2007) In addition, the lack of capelin in seabird diets during the 1990s in Labrador (Bryant & Jones 1999, Baillie & Jones 2004) is inconsistent with the non-collapse hypothesis.

Increases in seabird populations post-1991 were related to factors unrelated to availability of capelin as prey. For example, the population increase of common murres post-1991 has been associated with major reductions in adult mortality due to the coincident closure of the Atlantic salmon (*Salmo salar*) and Atlantic cod gillnet fisheries (Regular et al. 2013). The removal of thousands of gillnets from inshore areas during the 1990s and 2000s resulted in a significant reduction in bycatch mortality of breeding adult diving seabirds. Reductions in common murre adult mortality associated with ship-sourced oil pollution and hunting also decreased during this same period (Wilhelm et al. 2009). Increases in the populations of Atlantic puffins and northern gannets in the 1990s and 2000s were also associated with these same factors.

In summary, the trends in seabird abundance do not provide support for either the collapse or non-collapse hypothesis as other variables, such as removal of gill nets in the inshore area, had a larger impact on breeding adult seabird survival (Table 1). Seabird dietary information does not provide support for either hypothesis, but seabird diet did reflect the late inshore arrival of capelin post-1991 (Davoren & Montevecchi 2003, Gulka et al. 2017) and is consistent with changes in availability of various prey.

#### Zooplankton response: Calanus finmarchicus abundance

Given the magnitude of the capelin collapse, a significant increase in their main copepod prey, *Calanus finmarchicus*, might have been expected (e.g., Gjøsæter et al. 2002). Unlike the extensive zooplankton sampling effort in the Barents Sea, zooplankton on the NL shelf (Divs. 3KL) have only been sampled on a regular basis using plankton nets since 1999 (Fisheries and Oceans Canada’s Atlantic Zonal Monitoring Programme). The Continuous Plankton Recorder (CPR) dataset was used to test the non-collapse hypothesis, as it spans several decades, starting in the late 1950s,However, the usefulness of CPR data in tracking inter-annual changes in copepod abundance in the Northwest Atlantic has been questioned. Head and Pepin (2010) noted that only two years between 1960-1978 had more than 8 months of observations over the Grand Banks sections of the CPR sampling, which was the section used to test the non-collapse hypothesis, and inconsistencies in the course of the survey tracks from ships-of-opportunity resulted in uneven sampling of different water masses (Pepin et al. 2011). Furthermore, there was a substantial reduction in CPR mileage towed in the 1980s with a contraction of monitoring to 20° W in the eastern Atlantic (Reid et al. 2003); consequently, there is a large gap in CPR data from 1979-1990, which precluded its use in a recent capelin study (Mullowney et al. 2016).

In summary, CPR data cannot be used to support either hypothesis (Table 1).

#### Physical variability

The non-collapse hypothesis used an analysis of ocean climate to show a change in environmental conditions ~ 5 years after the proposed capelin collapse and concluded that the physical evidence for an environmental driver of capelin collapse was weak. Elsewhere in the literature, 1991, not 1996, has been identified as a climatologically important decadal signal due to its strong cold anomaly (e.g., Drinkwater 1996, Colbourne et al. 2014, Colbourne et al. 2016). The cold anomaly in 1991 was associated with a regime shift in the North Atlantic ecosystem that was characterized by the collapse of Atlantic cod, capelin and other commercial and non-commercial finfish species and correspondent increase in shellfish biomass (Lilly et al. 2000, Buren et al. 2014a, Pedersen et al. 2017); seabird dietary shifts from warm- to cold-water pelagic prey (Montevecchi & Myers 1992, Montevecchi & Myers 1997, Montevecchi 2007); and shifts in groundfish diet (Dawe et al. 2012).

In summary, this study’s findings show evidence of a capelin collapse that coincides with a regime shift, which is consistent with other studies that have attributed ecosystem-wide changes in the NL region to the cold water anomaly (Table 1).

## Discussion

The weight of evidence led us to conclude that the Div. 2J3KL capelin stock suffered a population collapse in 1990-91 with minimal recovery in the subsequent 25+ years. We found strong internal and external consistency in trends across multiple independent sources of data (Table 1). In particular, the spring acoustic survey effectively tracked capelin year classes and was strongly correlated to an independent inshore larval abundance survey. Moreover, we found strong agreement across independent acoustic surveys conducted in offshore waters. These acoustic surveys supported the scenario of a capelin stock collapse in the early 1990s, and subsequent surveys and data examined were not consistent with the possibility that millions of tonnes of capelin have been residing along the northeast coast of NL for almost three decades. Our conclusion is thus consistent with that of numerous past studies that concluded that the NL capelin stock suffered an order of magnitude decline in the early 1990s (DFO 1994, Miller 1994, 1997, Rose & O'Driscoll 2002, Davoren & Montevecchi 2003, Rose 2007, DFO 2008, 2010, 2013, Buren et al. 2014a, Mullowney & Rose 2014, DFO 2015, Murphy et al. 2018).

In contrast, the non-collapse hypothesis postulated that the capelin stock did not suffer a collapse but instead experienced a dramatic change in phenology post-1991, which reduced their vulnerability to existing surveys. Specifically, the non-collapse hypothesis states there was either (1) a spatio-temporal mismatch between the spring acoustic survey and capelin phenology; or (2) a change in the ecology of capelin from a highly migratory stock to one that resides year-round within poorly-surveyed inshore waters. The first hypothesis was rejected both by Frank et al. (2016) and our analyses. From our test of the second hypothesis proposing the inshore residence of 3-6 Mt of capelin, we concluded that there would have to be a minimum capelin biomass of 41,000 kg km-2 evenly distributed throughout the un-surveyed inshore area over much of the past 25 years to compensate for the “missing” offshore fish. Instead, seasonal inshore acoustic surveys in Trinity Bay revealed a maximum capelin biomass of 10,000 kg km-2 in June, and much lower densities outside of the peak spawning period. Most importantly, we conclude it is not plausible that 3-6 Mt of capelin distributed inshore would have gone unnoticed for more than 25 years by both DFO and fish harvesters from the numerous fishing communities that span the northeast coast of NL.

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## Tables

Table 1. Summary of the differing degrees of support that each line of evidence provides for the capelin collapse and non-collapse hypotheses. Degrees of support have been categorized into 6 classes; see key in the footnote

|  |  |  |
| --- | --- | --- |
| Evidence | collapse hypothesis | non-collapse hypothesis |
| Offshore Capelin Abundance | + | − |
| Analysis of ‘missing’ capelin distributed inshore | + | − |
| Offshore capelin distribution | + | - |
| Timing of capelin offshore residence | + | - |
| Independent indices of inshore capelin abundance | X | X |
| Inshore recruitment index | + | - |
| Temporal dynamics of cod weight-at-age and condition | + | - |
| Harp seal population trends and diet | + | - |
| Seabird population trends | = | = |
| Seabird diets | + | - |
| Zooplankton response: *Calanus finmarchicus* abundance | X | X |
| Physical variability | + | - |

+ Support in favor of hypothesis

+ Consistent with hypothesis

= Equivocal support

- Inconsistent with hypothesis

- Support against hypothesis

X Evidence cannot be used to test the hypotheses

## Figure captions

Fig. 1. Capelin stock area in NAFO Divisions 2J3KL including the embayments of Newfoundland, Canada. Included are the acoustic survey tracks conducted in Div. 3L (offshore) and Trinity Bay (inshore) in May 2018 by Canada (DFO, unpublished data); Div. 3LNO in June 1991 by the former USSR (see Bakanev 1992 for more details); Div. 2J3K in October 1983 by Canada (see Miller & Carscadden 1983 for more details); and Div. 2J3K in November 1991 by the former USSR (see Bakanev 1992 for more details).

Fig. 2. Trends in five acoustic survey indices: Div. 2J3K Fall Canada (1982-92), Div. 2J3K Fall USSR (1982-92), Div. 3L Spring Canada (1988-92, 1996, 1999-2005, 2007-15, 2017), Div. 3LNO Spring USSR (1975-94), and Trinity Bay (inshore Div. 3L; 1999-2005, 2007-13, 2017). The vertical lines indicate 95% confidence intervals of the index. Note the log scale.

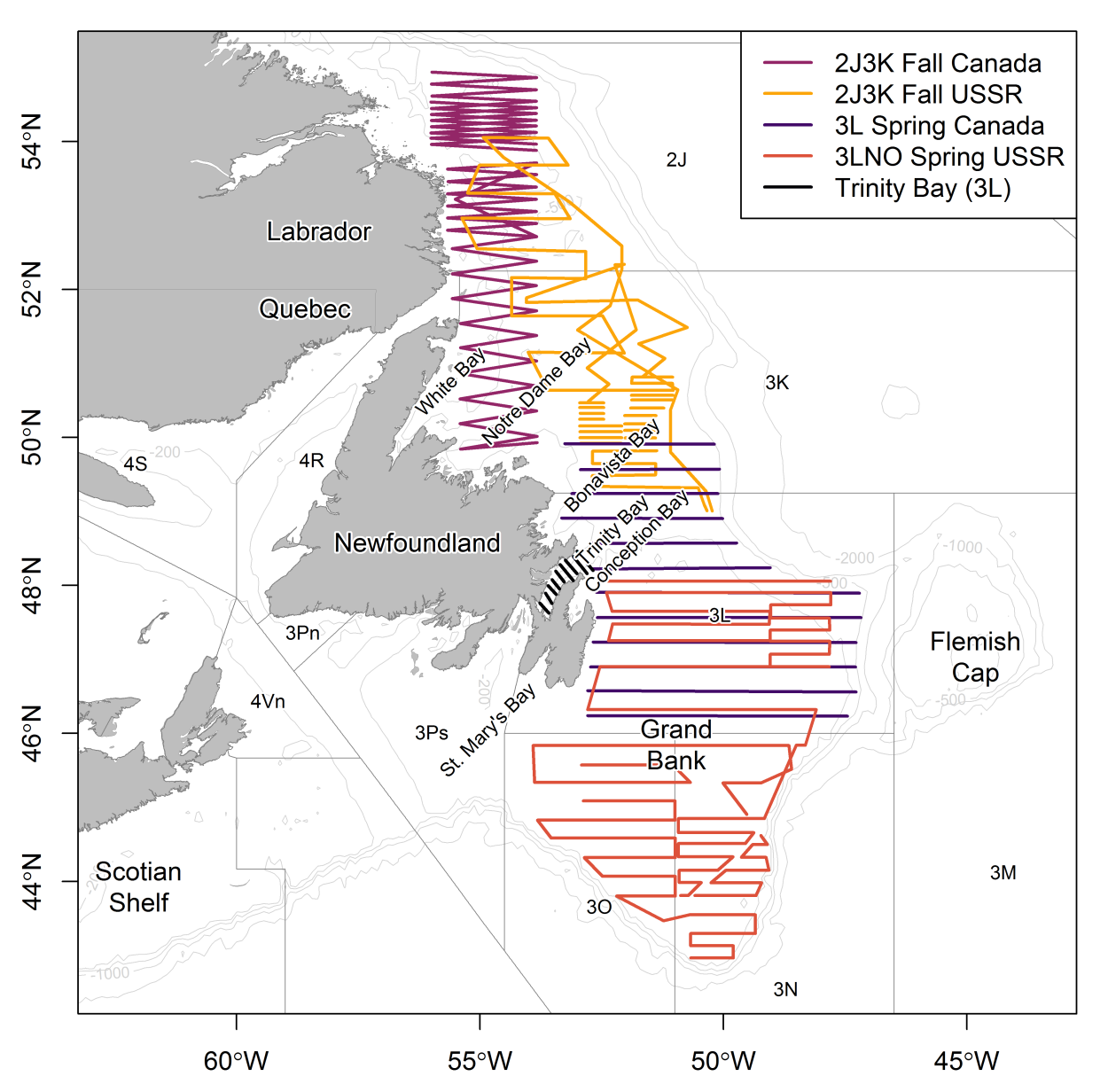
Fig. 3. (a) Capelin biomass (kg/ km-2) estimated from the seasonal inshore acoustic survey in Trinity Bay, NL, Canada. The May values are for the main portion of Trinity Bay only, while the other months surveyed the entire bay, including the arms and headland (note the log scale); and (b) capelin maturity stage composition (n = 5319) and (c) capelin age composition (n = 864) sampled in the seasonal inshore acoustic surveys in Trinity Bay in 2003-05. S/R is spent/recovering, Mat. is maturing, and Imm. is immature.

Fig. 4. Center of gravity analysis using the VAST package in R (Thorson et al. 2016, Thorson & Barnett 2017) using data from the fall bottom-trawl survey in NAFO Divisions 2J3KL (Newfoundland and Labrador, Canada; 1995-2017) to fit a geostatistical delta-generalized linear mixed model to estimate the spatial and temporal distribution of capelin. Annual center of gravity estimates are connected by lines through time, and approximate 95% confidence intervals around these estimates are indicated by the dotted black line. The red area indicates areas not covered by the survey and the light pink (cream) area indicates inshore strata that are poorly covered by the fall bottom-trawl survey.

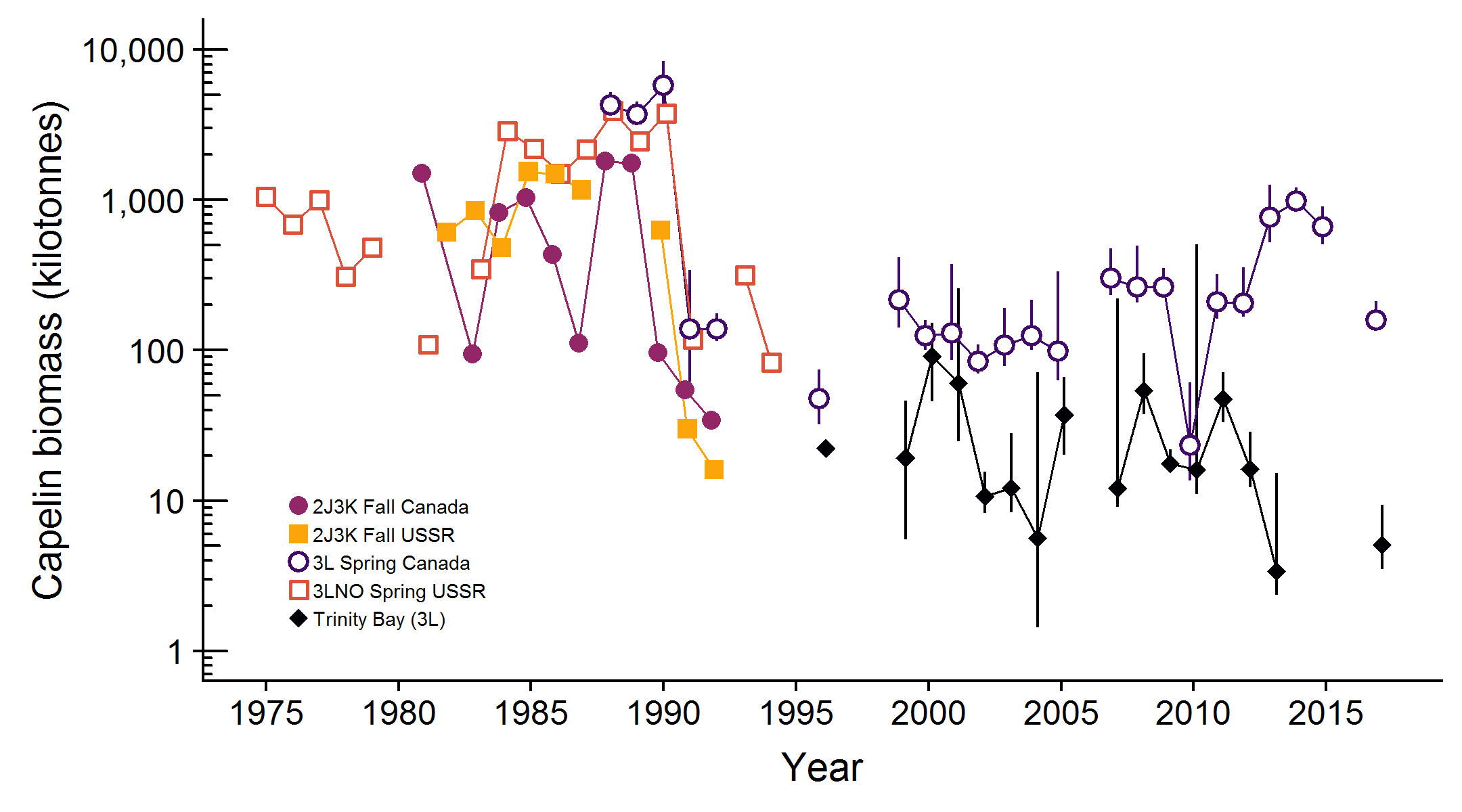
**Fig 5.**

**Fig. 6.**

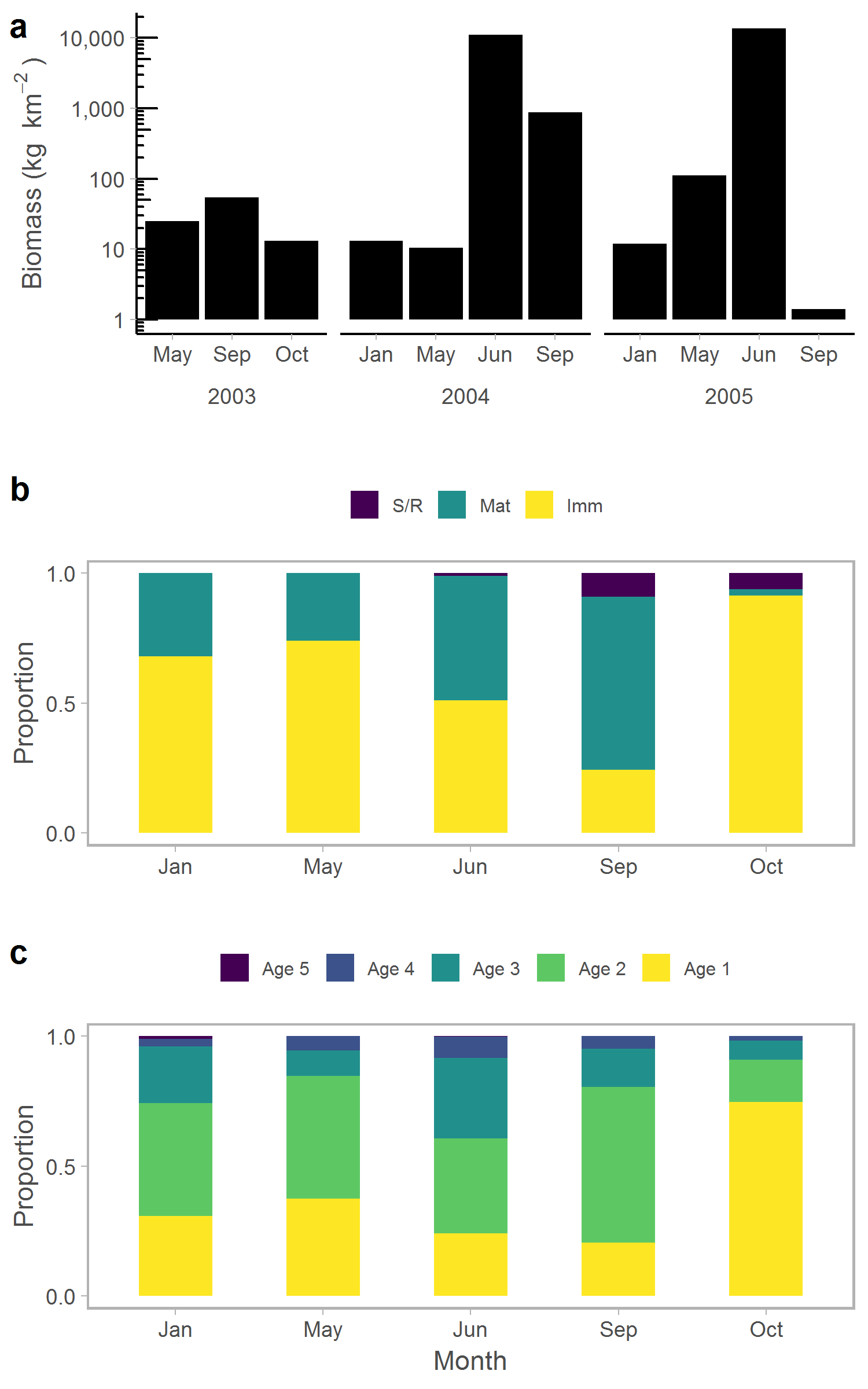
**Fig. 1**

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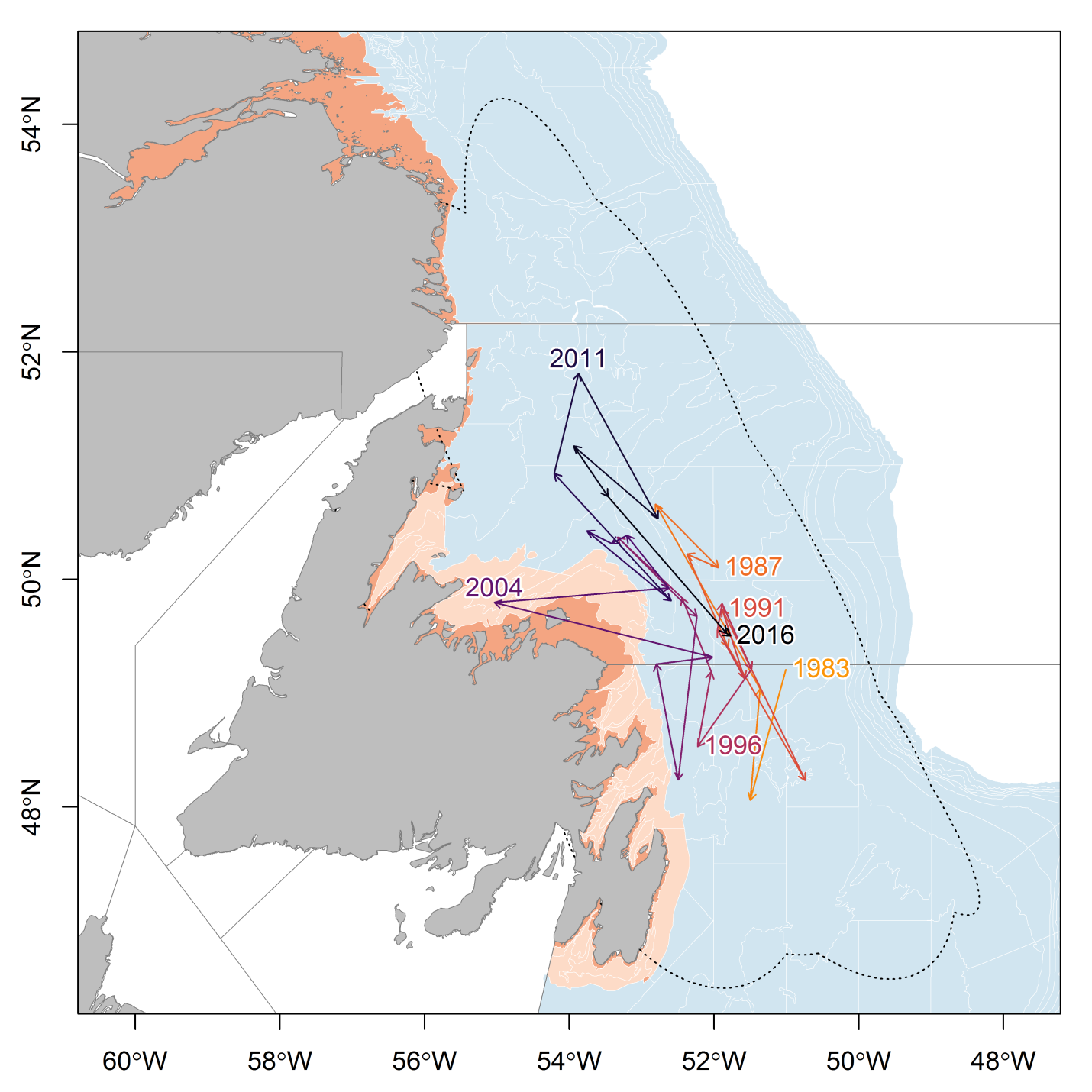
**Fig. 2**

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**Fig. 3**

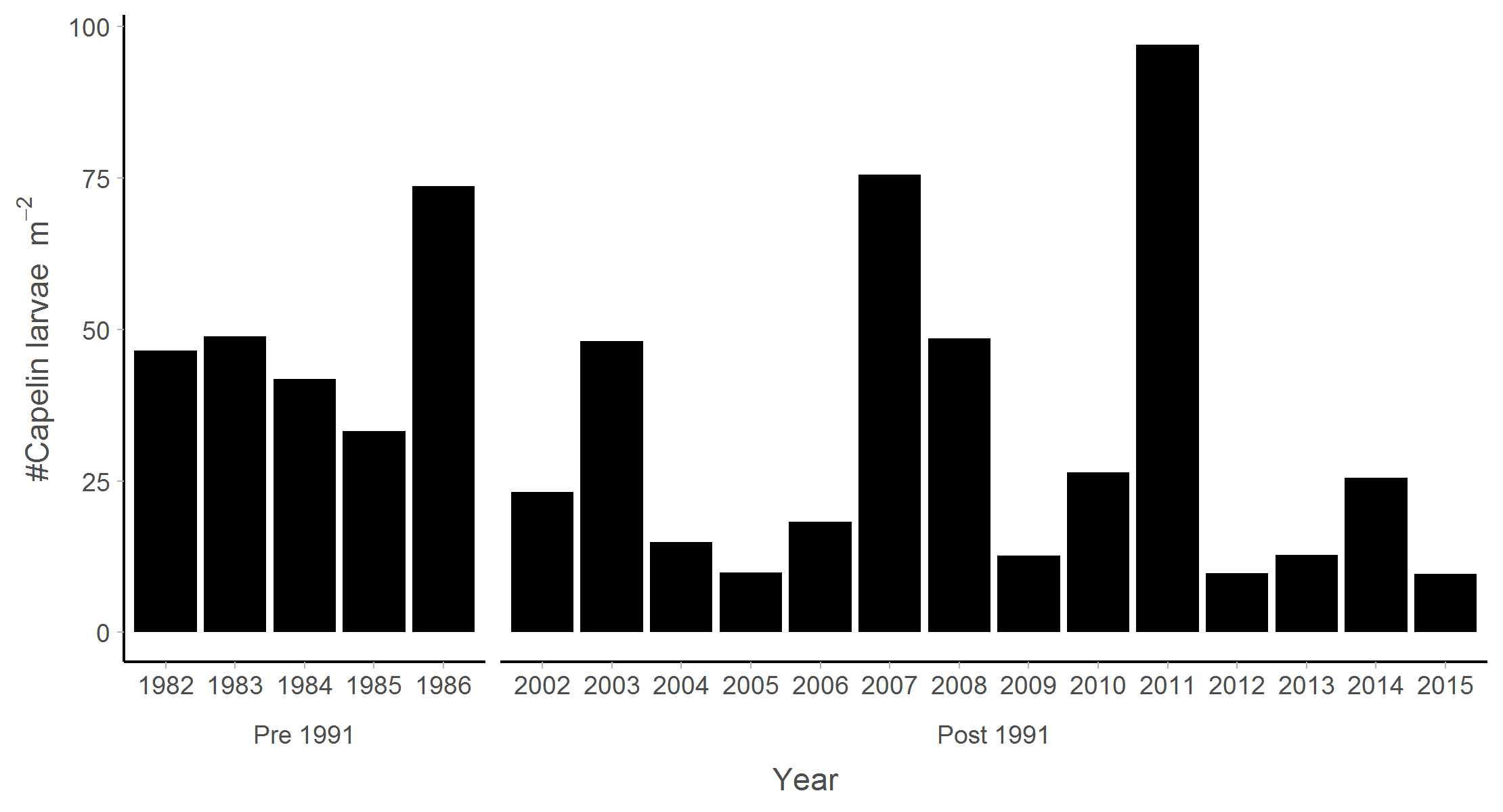
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**Fig. 4**

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**Fig. 5**

**Fig. 6**

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