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A pre-COSEWIC assessment of thorny skate (*Amblyraja radiata* Donovan, 1808) on the Grand Bank, Newfoundland Shelf, Labrador and northern waters

Évaluation pré-COSEPAC de la raie épineuse (*Amblyraja radiata* Donovan, 1808) dans les régions du Grand Banc, du plateau continental de Terre-Neuve, du Labrador et dans les eaux nordiques

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ABSTRACT

This paper presents the most recent information regarding the life history and fisheries of thorny skate (*Amblyraja radiata* Donovan 1808) in Newfoundland and Labrador waters, and includes available data from Arctic waters. The primary purpose of this paper is to provide this information to the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) for use in formulating and evaluating conservation and management strategies for this species in terms of risk of extinction.

Independent data series based on spring and fall bottom trawl research survey catches and commercial fisheries statistics covering the distribution of *A. radiata* in NAFO Div. 2HJ3KLMNOPs indicate that this species is widely distributed from Baffin Bay to the Laurentian Channel, but that its main stock component is consistently found on the Grand Bank over time. Research survey indices of relative abundance and distribution varied little since the 1970s in Div. 3OPs (southwestern Grand Bank and Laurentian Channel); whereas in Div. 3LN (northern and eastern Grand Bank), *A. radiata* experienced considerable declines in abundance and area occupied during the early 1990s. However, common features were also detected throughout the study area; notably in terms of thermal preferences and a recent increasing trend in indices of relative abundance. The latter constitutes a first sign of stock recovery in most areas during the last decade.

Several important aspects of the life history and fisheries of *A. radiata* in the study area remain uncertain or are lacking; largely due to partial knowledge of population structure and biology, as well as the impacts of commercial fisheries and environmental variability.

RÉSUMÉ

Ce document présente la plus récente information concernant l'historique de vie et la pêche de la raie épineuse (*Amblyraja radiata* Donovan 1808) dans les eaux de Terre-Neuve et du Labrador; il comprend également les données disponibles pour les eaux de l'Arctique. L'objet principal de ce document est de fournir cette information au Comité sur la situation des espèces en péril au Canada (COSEPAC) en vue de leur utilisation pour l'élaboration et l'évaluation des programmes de conservation et de gestion de cette espèce en ce qui a trait au risque d'extinction.

L'ensemble de données indépendantes reposant sur les captures des relevés de recherche de chalut de fond du printemps et de l'automne et sur les statistiques des pêches commerciales relativement à la distribution de l'espèce *A. radiata* dans les divisions 2HJ3KLMNOPs de l'OPANO indique que cette espèce est grandement répartie de la baie de Baffin jusqu'au chenal Laurentien, mais, qu'au fil du temps, on retrouve constamment la principale partie des stocks sur le Grand Banc. Les indices de relevés de recherche sur l'abondance relative et la distribution ont peu varié depuis les années 1970 dans la division 3OPs (sud-ouest du Grand Banc et chenal Laurentien), tandis que dans la division 3LN (nord et est du Grand Banc), l'espèce *A. radiata* a connu une baisse considérable par rapport à son abondance et à l'aire occupée au début des années 1990. Cependant, on a également décelé des caractéristiques communes dans toute la zone étudiée, notamment en ce qui a trait aux préférences thermiques, et une récente tendance à la hausse des indices d'abondance relative. Ce dernier élément constitue un premier signe du rétablissement des stocks dans la plupart des régions au cours de la dernière décennie.

Plusieurs aspects importants de l'historique de vie et de la pêche de l'espèce *A. radiata* dans la zone d'étude demeurent incertains ou sont manquants, ce qui est en grande partie dû à une connaissance partielle de la structure et de la biologie de la population, ainsi qu'aux répercussions de la pêche commerciale et à la variabilité de l'environnement.

INTRODUCTION

Thorny Skate (*Amblyraja radiata* Donovan 1808, Family Rajidae) is an endemic and widely distributed skate species in the North Atlantic Ocean (Fig. 1). Similar to many other elasmobranch species, *A. radiata* is considered to have low reproductive potential resulting from slow growth, late sexual maturation, low fecundity, and long reproductive cycles (Templeman 1987*a;* del Río and Junquera 2001*a*); probably rendering this species highly vulnerable to exploitation. Accordingly, the International Union for the Conservation of Nature (IUCN) has listed *A. radiata* as Vulnerable on their Redlist: a global assessment of risk of extinction (Kulka et al. 2004*a*), and in Canada, COSEWIC (Committee on the Status of Endangered Wildlife in Canada) will evaluate the status of *A. radiata* in terms of risk of extinction.

This paper presents the most recent information regarding the life history of this species: including growth, maturity, population structure, and other information for use in formulating appropriate conservation and management actions in terms of extinction risk. The primary purpose of this paper is to provide this information to COSEWIC for its evaluation of risk of extinction for *A. radiata*; focussing on the Grand Bank to Labrador Shelf, and NAFO Subarea 0 and Hudson Strait.

SPECIES TRAITS

Taxonomy

Other common names for *A. radiata* include Starry Ray (Northeast Atlantic), Starry Skate, Maiden Ray, Miller Ray, raie épineuse (French), and raya radiante (Spain). Synonyms are *Raia americana* (DeKay 1842), *Raia scabrata* (Garman 1913), and *Raja radiata* (Donovan 1808). Garman (1913) differentiated Northwest from Northeast Atlantic Thorny Skate by naming it as a new species, but Bigelow and Schroeder (1953) restored the original name to its entire range; not finding significant differences between areas. This rather complex taxonomic history may be due in part to its phenotypic plasticity and variable growth rates.

Distribution

A. radiata is found in north temperate to Arctic regions, in the northeast Atlantic from the White, Barents and Black Seas, as far south as the North and Irish Seas, and westward around Iceland and southern Greenland (ICES 2005; Fig. 1). In the western Atlantic, it is distributed from Greenland to South Carolina. In Canadian waters *A. radiata* is distributed continuously throughout most of the continental shelf, from the high Arctic off of Baffin Island (Davis Strait, Hudson Strait, Ungava Bay), south along the Labrador Shelf, northeast Newfoundland Shelf, the Grand Banks, Gulf of St. Lawrence, Scotian Shelf, Bay of Fundy, and Gulf of Maine (Sulak et al. 2009). At the centre of its distribution on the Grand Bank, it is densely concentrated on the southern part of the Bank (Kulka and Miri 2003).

Morphology, Morphometric and Meristic Characteristics

A. radiata is a medium-sized species, but its maximum size varies between areas: reaching 90 cm (7.5 kg) on the Labrador Shelf, 110 cm (12.5 kg) on the Grand Bank (Templeman 1987*b*; Kulka et al. 2004*b*), and approximately 100 cm (10 kg) in the Gulf of St. Lawrence, Scotian Shelf, and Gulf of Maine (Sulikowski et al. 2005; McPhie and Campana 2009*a*). Maximum length in the Northeast Atlantic is approximately 90 cm (Stehmann and Bürkel 1984).

Sulak et al. (2009) described *A. radiata* with a spade-shaped to heart-shaped body (disc), snout and wings (pectoral fins) rounded, tail 1-1.1 times body length with a distinctive banding pattern, a dominant mid-dorsal row of 11-19 large thorns bearing radiate bases (with 10 or fewer thorns behind the pectoral axil), usually 3 large thorns around each eye, 1-3 thorns on each shoulder, a variable patch of large thorns medially on each wing, centre of the disc smooth between large thorns, and small juveniles with tiny dark spots and extremely sharp spines on their dorsal discs (Fig. 2). A primary characteristic that distinguishes this species from other skates occurring in Canadian waters is the row of 11-19 large thorns on the midline of its back and tail (before the first dorsal fin).

Although Sulak (ibid.) reported that *A. radiata* dorsal fins are separated by a distinct gap with no intervening thorn, and that its dorsal (upper) surface is gray to brown (uniform or mottled), these characteristics are highly variable in Northwest Atlantic specimens: ranging from completely joined dorsal fins (i.e., with no spines between them), to a large gap with 0-5 spines between them (C. Miri unpubl.). The dorsal surface of this species can also vary from yellow-edged dark pseudo-rosettes on light brown, to an almost uniform dark brown (ibid.). Therefore, dorsal pigmentation and patterning are not reliable characteristics for identification of *A. radiata*. Its ventral surface is uniformly white; rarely with a few small, non-symmetrical, darkly-pigmented markings.

Population Structure

A. radiata show considerable variation across their distribution range; suggesting that mixing is minimal and that the species does not move any great distance - individually or over many generations. Templeman (1987*b*) examined length-weight relationships of *A. radiata* throughout Canadian waters and found small but statistically significant differences: fish from the Labrador Shelf were smaller, and mature at a smaller size when compared to fish from the Grand Bank. In addition, there are noticeable latitudinal differences in mean weight of fish, maximum size, and size at maturity at the northern edge of the Grand Bank (Lat. 49^{o}). Fish to the north of this boundary were on average 1.1 kg lighter (equivalent to 13 cm in length), and onset of maturity occurred at approximately 40 cm; nearly 20 cm less than to the south. Templeman (1984*b*) also noted that no large scale migrations occurred between these areas, supporting the view that limited mixing has likely contributed to observed local patterns.

Analysis of several meristic measurements carried out by Templeman (1984*a*, 1987*b*) provided no evidence of variation across the Grand Bank. However, Templeman (1984*a*) showed a latitudinal cline of mean number of median dorsal thorns from Baffin Island southward to the Grand Bank, the Gulf of St. Lawrence, Scotian Shelf, and Georges Bank: higher numbers occurred at lower developmental temperatures and *vice versa*. Mean tooth-row counts showed a cline which was opposite to that of median dorsal thorns. In addition, Templeman (1987*b*) examined nineteen morphometric characteristics and noted that the species became less thorny with age.

Tagging studies conducted with *A. radiata* indicated maximum travelling distances of individuals as hundreds of kilometres; but usually much less (Templeman 1984*b*). This situation may promote phylogenetic differentiation over the long term. Therefore, it seems highly unlikely that *A. radiata* have mixed across the Atlantic Ocean, from the USA to the Barents Sea; even over many generations.

However, Chevolot et al. (2007) conducted the only study to date examining population structure of *A. radiata* through the use of genetic analysis. This work indicated almost an absence of genetic differentiation in populations across the North Atlantic. However, they did note that the analysis lacked explanatory power, due to the small sample size in some cases (e.g., only one sample from Canadian waters off of Newfoundland). The authors suggested that, given such genetic homogeneity, the range of movement of *A. radiata* may be greater over many generations, because dispersion may increase incrementally over many generations; thus facilitating mixing of genetic material.

Age and Growth

Skates have been aged using vertebrae (McEachran 1973; Gallagher et al. 2005; Gedamke et al. 2005; Sulikowski et al. 2005; Tsang 2005; McPhie and Campana 2009*a*), and caudal thorns (Gallagher et al. 2002; Henderson et al. 2005). On the Scotian Shelf to the south of the Grand Bank, McPhie and Campana (2009*a*) suggested that *A. radiata* reach an absolute age of at least 28 years: the oldest validated age reported for any batoid fish species. They also suggested a theoretical maximum age of 39 years; obtained using Taylor's equation (Taylor 1958). However, the oldest fish in that study was 19 years (83 cm). A long-term tagging study by Templeman (1984*b*) indicated that *A. radiata* live at least 20 years; supporting the view of a long lived species (although maximum age remains uncertain).

McPhie and Campana (2009*a*) noted that *A. radiata* on the Scotian Shelf can be considered a relatively slow-growing elasmobranch with a growth coefficient K=0.07; according to the von Bertalanffy growth model (VBGM). Growth parameters differed in magnitude from those reported from other locations (i.e., slower growth; greater maximum age). In the Gulf of Maine, Sulikowski et al. (2005) also fitted a VBGM, and indicated that female asymptotic length was L_∞ =120 cm and K=0.13. However, the oldest fish in that study was 16 years, and smaller (105 cm) than the calculated L_∞.

Reproduction

A maturity study on *A. radiata* in the Northwest Atlantic Ocean was first undertaken by Templeman (1987*a*), based on fish collected in 1947-72. Although details of various reproductive parts examined were provided, there was no explicit description of what determined a mature fish; even though Templeman indicated that 22 % of females classified as mature had developing or fully-formed egg cases. Templeman (ibid.) also showed that sexual maturity and maximum length occurred at smaller sizes on the northeast Newfoundland Shelf to west Greenland, as compared to those on the Grand Bank; in addition to observed differences in female egg volume, shell glands, male clasper length, and pectoral fin rows of alar spines (i.e., used by males during reproduction) between those regions. Female length at 50 % maturity (L_{50}) from Baffin Island to the Labrador Shelf was found to be approximately 45 cm; similar to west Greenland and Iceland. This metric compared to almost 48 cm on the northeast Newfoundland Shelf, 70 cm on the Grand Bank, and 51 cm in the Gulf of St. Lawrence.

del Río and Junquera (2001*a*) used macroscopic observation of maturity stages and determined L_{50} to be 54 cm (1997), 55 cm (1998), and 60 cm (2000); indicating a range of values between years. This finding was considerably lower than what Templeman (1987*a*) observed for the Grand Bank in his multi-decadal study (L_{50} =70 cm). Therefore, it appears that *A. radiata* on the Grand Bank may have matured at a smaller size in the late 1990s; or alternatively, maturity determination methodology differed between studies, and thus yielded different results.

On the Scotian Shelf (south of the Grand Banks), McPhie and Campana (2009*b*) found that female *A. radiata* matured over a wide range of sizes, and estimated L_{50} =51.4 cm (11 years old): a size more closely associated with the Gulf of St. Lawrence and the northeast Newfoundland Shelf, but smaller than fish on the adjacent Grand Bank. In the Gulf of Maine, Sosebee (2002) estimated L_{50} =50 cm; similar to the size observed on the Scotian Shelf. In a subsequent study, Sulikowski et al. (2005) estimated a much larger L_{50} =87.5 cm (11 years old);

using gross reproductive morphology, histology, and steroid hormone concentrations as criteria to examine maturity. The above studies suggest that L_{50} for this species varies considerably; not only spatially but also temporally, and that using a single value for maturity determination will likely result in bias.

Regarding spawning period, Templeman (1984*b*, 1987*a*) determined that reproduction occurred year round in Canadian waters; but del Río and Junquera (2001*a*) indicated that peak spawning occurred in autumn and winter. In addition, del Río (2002) examined *A. radiata* females on the Grand Bank for presence of egg capsules in the oviducts, numbers and sizes of eggs in the ovaries, and variations in the width of shell glands. These studies confirmed the low reproductive potential of this species, and that both number and size of oocytes developing in the ovaries increased in maturing fish. In fully mature skates, number of eggs in the ovaries was 40-45, and egg diameter averaged approximately 12 mm. A majority of adult females had mature ovaries in August-December; but active uterine stages were almost absent. Most males were mature during the same period.

Templeman (1982*a*, 1987*a*) also examined the development and characteristics of *A. radiata* egg cases ("Mermaid's purses") in the Northwest Atlantic. These studies found that females carrying egg cases were found throughout the distribution of this species, and in all months of the year; indicating that reproduction was widespread, both spatially and temporally. Ovaries of sexually mature females often held 10-12 pairs of eggs in different developmental stages, with synchronous formation of egg case pairs in the oviducts (Hobson 1930; Chinarina and Troschicheva 1980; Templeman 1982*a*). A mature egg is liberated from each of the ovaries, fertilized in the upper part of each oviduct, and then enclosed with yolk and albumen in an egg casle (Clark 1922).

Templeman (1982*a*, 1987*a*) reported that a female can deposit 6-40 egg cases per year (each containing a single embryo), and between 41-56 per year on the Scotian Shelf (McPhie and Campana 2009*b*). Larger females produce larger eggs, but it is not known if egg case size is related to survival rate of the hatchling. Upon hatching, young skates are fully developed, and survival is much greater than eggs released by teleosts. However, knowledge of early life history of *A. radiata* is limited. Berestovskii (1994) looked at reproductive aspects under experimental conditions, and hatched eggs collected from the southern Barents Sea. Berestovskii (ibid.) speculated that, at low temperatures, embryonic development in extruded egg cases could extend over 2-2.5 years in the Barents Sea, where thermal conditions are similar to the shelf waters off Newfoundland. At hatching, these skates were 10.4-11.4 cm in total length (TL), with body (disc) widths of 6.2-6.9 cm, and weighing 7.8-10.5 g. Newly hatched individuals had an internal yolk sac, a site of umbilicus attachment, and a "larval" tail piece of approximately 8 mm in length.

Overall, the above studies indicated that growth and reproduction are highly variable in *A. radiata*, are affected by local conditions, and that maturity occurs over a wide range of sizes.

Diet

Several diet studies have been published for *A. radiata* populations in the Northwest Atlantic Ocean. In the northeastern USA and southern Canada, this species was observed to have a diversified diet of both epifauna and infauna: feeding largely on decapod crustaceans, euphausiids, and polychaetes (McEachran et al. 1976). This diet was thought to reflect habitat associations. Templeman (1982*b*) examined diet in areas further north, from Georges Bank to Greenland, and noted that stomach contents consisted mainly of small pelagic fish like Northern Sand Lance (*Ammodytes dubius*), Capelin (*Mallotus villosus*), decapods (Spider and Hermit Crabs, pandalid shrimp), cephalopods, polychaetes, and amphipods. Smaller skates had higher proportions of cephalopods, polychaetes, and amphipods. Garrison and Link (2000) examined dietary guild structure of fish off of the northeast USA, and found *A. radiata* to be a benthivore, feeding on a wide range of fish species; notably Haddock (*Melanogrammus aeglefinus*), various flounders, Scup, and Croaker. A more recent study on the Grand Bank (González et al. 2006) found that feeding intensity was high (84 % of stomachs examined contained food), and that *A. radiata* had a wide prey spectrum (i.e., ninety species identified) as compared to other skate species, which fed primarily on fish and crustaceans. The proportion of fish and molluscs in the diet increased with skate body size. Specifically, Northern Sand Lance and Snow Crab (*Chionocetes opilio*) were the two most important prey on the Grand Bank. To the north off of Greenland, Greenland Halibut (*Reinhardtius hippoglossoides*), Blue Ling (*Micromesistius poutassou)*, pandalid shrimp, and a small octopus (*Bathypolypus arcticus*) were dominant in the diet of *A. radiata*.

These studies indicated that *A. radiata* has a highly varied diet of fish and invertebrates, but that proportion of various prey types changes according to geographical location and skate body size.

<u>Parasites</u>

The only study that dealt with parasites of *A. radiata* was Randhawa et al. (2007), who surveyed tapeworm infestation in the Bay of Fundy.

FISHERY AND MANAGEMENT

Kulka and Mowbray (1999) reported significant bycatches of skates in Canada since the commencement of offshore fishing in the late 1940s. The skate fishery was dominated by non-Canadian fleets prior to the mid-1980s, which kept and processed several thousands of tons annually. In 1985, Spain began targeting skates in a non-regulated fishery outside Canada's 200-Mile-Limit (i.e., in the NAFO Regulatory Area or NRA) on the Tail of the Grand Bank (Junquera and Paz 1998; del Río and Junquera 2001*b*). In 2000, Russia commenced a directed fishery for *A. radiata* (Vinnichenko et al. 2002). Other countries, especially Portugal, continue to report skate catches to the Northwest Atlantic Fisheries Organization (NAFO); primarily as bycatch in other commercial fisheries of the NRA.

In the early to mid-1980s, unspeciated skates were taken annually as bycatch in Canadian offshore fisheries, but were mostly discarded (Kulka 1982, 1984, 1985, 1986*a*, 1986*b*, 1989). In 1995, Canada established a regulated skate-directed fishery inside its 200-Mile Limit (i.e., Canada's Exclusive Economic Zone) with gear and bycatch policies, licensing system, and Total Allowable Catch (TAC). While the Canadian skate fishery inside the EEZ was regulated by quota, skate fisheries in the NRA remained unregulated until 2005. In 2005, NAFO began managing this stock in the NRA, and a skate quota of 13,500 t was set for Div. 3LNO. The NAFO skate TAC was lowered to 12,000 t for the 2010 and 2011 seasons.

A. radiata have been targeted in other areas of the Northwest Atlantic: on the Scotian Shelf, in NAFO Subarea 1 (off of west Greenland), and in Subarea 0. *A. radiata* was also taken as bycatch in numerous other demersal fisheries. In the Gulf of Maine, it was one of four skate species regarded as overfished (Northeast Fisheries Science Center 2000; New England Fishery Management Council 2001).

MATERIALS AND METHODS

SURVEYS

NL Region

Bottom trawl surveys have been conducted throughout the continental shelves of Newfoundland and Labrador in spring (1971-2010) and fall (1977-2010). The surveys were originally designed to provide estimates of abundance for major groundfish species such as Atlantic Cod (*Gadus morhua*), and Redfish (*Sebastes sp.*). However, *A. radiata* distributes in similar depth and latitudinal ranges and thus, the survey footprint adequately covers the distribution range of this species in the NL Region.

Demersal trawl surveys in the NL Region employ a random stratified design, with fishing tow allocation based on depth intervals and location (latitude and longitude; Fig. 3). A summary of the survey design employed in the NL Region since 1970 can be found in Doubleday (1981).

Fall surveys in NAFO Div. 2J3K were conducted by RV *Gadus Atlantica* until 1994. In 1995-2000, they were conducted mainly by RV *Teleost*; although RV *Wilfred Templeman* surveyed part of Div. 3K. NAFO Div. 3L surveys were conducted by RV *A.T. Cameron* (1971-82), and RV *Wilfred Templeman* or its sister ship RV *Alfred Needler* (1985-2000 in spring; 1983-2000 in fall). In recent years, RV *Teleost* surveyed a portion of Div. 3L. The fall survey was also extended into NAFO 3NO in 1990, using the RV *Wilfred Templeman.* Several demersal fishing gears have also been deployed over the lifetime of the surveys (Table 1): Yankee 41.5 bottom trawl for spring surveys until 1982; Engel 145 Hi-lift for fall surveys in 1977-94 and spring surveys in 1983-95; and Campelen 1800 shrimp trawl for fall of 1995 and spring 1996 to present. While survey design has remained constant, additional strata have been included in recent years; along with modifications to some of the original strata (Bishop 1994). One significant change in the surveys was the addition of shallower (<50 m) and deeper strata (>700 m) after 1993; although tows at depths <50 m were occasionally recorded in earlier years. It should be noted that no conversion factors exist between gears for *A. radiata*; therefore, each time series should be considered independently.

Central and Arctic Region

Depth-stratified random surveys covering depths from 400 m to 1500 m were conducted by DFO with an Alfredo-III bottom trawl in NAFO Subarea 0A (1999, 2001, 2004, 2006, 2008), Subarea 0B (2000, 2001), Shrimp Fishing Area (SFA) 1 (2007, 2009), and SFA 2 and 3 (2005-09). The 2006 and 2008 surveys included tows in shallower strata (100-800 m), using a Cosmos shrimp trawl. These surveys were conducted by DFO in collaboration with Nunavut partners and the Greenland Institute of Natural Resources. Surveys were carried out with the Greenlandic RV *Paamiut*.

Other Surveys of Interest

Additional independent scientific surveys have been conducted by other countries within or adjacent to the study area; often using the same stratification scheme as applied by Canada. Waters adjacent to the Canadian EEZ were surveyed by Spain (Instituto Español de Oceanografía, Far Fishery Program Communication), covering the “Nose” and “Tail” of the Grand Bank (NAFO Div. 3L and 3NO; Roman et al. 2010; González-Troncoso et al. 2010), and the Flemish Cap (Div. 3M; Pérez-Rodriguez and Koen-Alonso 2010). Russia and France have also conducted surveys within the study area. In addition, Greenland has conducted an annual bottom trawl survey off west Greenland since 1988 in waters adjacent to the study area (Nygaard and Jorgenson 2010).

Spatial distribution and habitat associations

Geo-referenced catch and hydrographic data for the spring and fall bottom trawl surveys were used to assess the spatial distribution and habitat associations of *A. radiata* throughout the study area. First, maps of the geographic distribution of standardized catch rate (kg/tow) were plotted using data from all surveys. The plots were grouped by season and into two 5-year periods; except for the spring survey series during the 1990s, which were grouped for the periods 1990-95 and 1996-99. The periods were chosen to correspond to changes in fishing gear types; in particular from Engel to Campelen trawl in 1995-96. The cumulative distribution of catch rate was also plotted for juveniles and adults (number of fish per tow). Due to considerable discrepancies about size at maturity (mentioned above), a threshold size of 54 cm separating immature and mature male and female *A. radiata* was assumed in this study.

The distribution of catch in relation to depth and temperature was also investigated. At each tow location, depth and bottom temperature were recorded using trawl-mounted sensors (SIMRAD depth sounder; Seabird 19 CTD). Plots of mean catch rate in relation to tow depth and temperature were produced for each NAFO Division, year, and season.

Area of occupancy

The area of occupancy (A_t) was calculated in each year t as follows:

$$(1) \qquad A_t = \sum_{k=1}^{S} \sum_{j=1}^{N_k} \sum_{i=1}^{n_j} \frac{a_k}{N_k n_j} I \quad \text{where } I = \begin{cases} 1 \text{ if } Y_{ijkl} > 0 \\ 0 \text{ otherwise} \end{cases}$$

where Y_{ijkl} is the number of fish in length interval l caught in tow i at site j in stratum k, a_k is the area of the stratum k (km^2), N_k is the number of sites sampled in stratum k, n_j is the number of tows conducted at site j, and S is the number of strata. A_t was calculated based on the *Index Strata* (i.e. those sampled throughout the time series), and sufficient data were available to conduct the analysis for three different regions: NAFO Div. 2J3K (fall), Div. 3LNO (spring and fall) and Subdiv. 3Ps (spring).

Abundance indices and size composition

Abundance and biomass have been estimated by areal expansion of the stratified arithmetic mean catch per tow (Smith and Somerton 1981). Survey indices were expressed as the mean fish number and weight (kg) per standard tow and reported for spring (NAFO Div. 3LNOPs) and fall (Div. 2HJ3KLMNO). Total abundance at length was calculated as the sum of the strata estimates for each length group over the survey area. Estimation was also done separately for juveniles (<54 cm) and adults (≥54 cm), and indices were expressed as number per tow. To estimate abundance in number and biomass over a constant sampling area, only strata sampled throughout the time series were included. In addition, each stratum had to be sampled at least twice a year.

COMMERCIAL FISHERIES REMOVALS

Information on skate removals by commercial fisheries were obtained from three data sources. The first was the DFO Zonal Interchange Format (ZIF) database, which was created in 1985 to record data on Canadian landings (recorded in fishers' logbooks and on fish plants' purchase slips). The second data source was the DFO Observer Program - Science database, which contains tow-by-tow information collected at sea in a standardized format by trained Canadian Fisheries Observers. This database was used here to investigate commercial discards of *A. radiata* at sea during 1985-2010. The third data source was the STATLANT-21A database maintained by the Northwest Atlantic Fisheries Organization. This database contains commercial catches from outside Canada's 200-mile limit, as reported by member countries. The latter was used here to estimate non-Canadian removals of *A. radiata* in 1960-2009, and Canadian catches for 1960-84.

The Fisheries Observers database was used to generate maps of the geographic distribution of *A. radiata* standardized catch rates [catch (kept+discard in kg) / tow duration in hours] for bottom trawl fisheries directing for skates, Atlantic Cod (*Gadus morhua*), Redfish (*Sebastes sp.*), American Plaice (*Hippoglossoides platessoides*), Witch Flounder (*Glyptocephalus cynoglossus*), and Yellowtail Flounder (*Limanda ferruginea*); using the same approach as for research survey data. Resultant distributions were then compared.

An index of exploitation or relative F was calculated for each NAFO Division and all areas combined; using a ratio of reported commercial catch to spring research survey biomass index. Indices for the Canadian fleet inside 200 miles (Div. 3LOPs) were then compared to indices for non-Canadian fleets fishing outside 200 miles (Div. 3N). Information on sizes of caught skate (unspeciated) is available from different sources, but mainly from National Research Reports. However, total lengths for *A. radiata* in commercial catches from various gear types were measured only sporadically; with most of the sampling done in 2000-03.

RESULTS

DISTRIBUTION AND HABITAT ASSOCIATIONS

A. radiata are distributed continuously throughout most of the continental shelf, from the high Arctic off of Baffin Island (Davis Strait, Hudson Strait, Ungava Bay), south along the Labrador Shelf, northeast Newfoundland Shelf, the Grand Banks, and onto the eastern edge of St Pierre Bank along the Laurentian Channel (Fig. 4). However, survey catch data indicate that the distribution of *A. radiata* on the Grand Bank (Div. 3LNO) has changed over time. During the 1970s and 1980s, *A. radiata* concentrations were more widespread and occupied most of the Grand Bank; but abundance declined in the northeast Grand Bank in the late 1990s, and became more concentrated along the southwest extent of the Grand Bank.

According to Kulka et al. (2004*a*), the proportion of surveyed area devoid of skates was 2 % in 1980-88, and almost 60 % of *A. radiata* caught during the surveys were located in 20 % of the surveyed area, and concentrations of skate were spread over the entire Grand Bank. By 2005 surveyed area devoid of skates reached 22 %, and concentrations became increasingly aggregated as 78 % of skates captured were concentrated in 20 % of the surveyed area. Currently, the Grand Bank is clearly demarcated into an area of high concentration in the south, and one of low density in the north. These changes are considered to be recent (Kulka et al. 1996*a*, 2004*a*). In contrast, concentration patterns have remained largely unchanged over the northern and southern areas of the distribution range.

Survey catch distribution

The distribution of catch from Canadian spring and fall surveys supported the view of the existence of one major concentration of *A. radiata*. According to catch distributions from both series, the concentration has its centre of distribution located over the Grand Bank in NAFO

Div. 3LNO and extending into Subdv. 3Ps along the shelf slope (Fig. 5). Fall plots confirm mostly low fish densities elsewhere (<1 kg/tow); except in the Hopedale Channel area (Div. 2H), where several high density tows (>10 kg/tow) occurred through the time-series. It suggests the existence of another much smaller fish concentration centered in the channel. For the periods (1980s onwards) and areas when comparisons are possible, no major seasonal differences in density and distribution patterns are evident on the Grand Bank; except for Div. 3N in 1990-95, when high densities are found over most of the Bank in fall only. Notwithstanding, beginning in the early 1990s, important declines in both fish density and extent of distribution occurred in the northern and eastern Grand Bank areas (Div. 3LN), which have persisted since then. High density tows have been mostly absent from these areas; except along the eastern Shelf edge from 2000 onwards. The detected changes happened several years prior to the surveys changing from Engel to Campelen trawl (1995-96), and thus were not related to changes in gear type. In contrast, density and distribution patters (spring and fall time series) varied little in areas encompassing the southern and western Grand Bank and adjacent areas (Div. 3NOPs), as well in Div. 2HJ3KM (fall time series), and increasing trends have been recently detected in most of these areas.

The cumulative distributions of spring (1999-2010) and fall (1981-2010) bottom trawl survey catch rates for juvenile (<54 cm) and adult (≥54 cm) *A. radiata* indicated noticeable seasonal and size-dependent differences in distribution (Fig. 6). On the Grand Bank, higher catch rates of adult fish occurred in deeper waters along the southwest shelf slope in spring (Div. 3O), and in shallower areas of the bank in fall (Div. 3NO). Similarly, higher catch rates of juvenile fish (mostly from the period prior to 1999) were observed in shallower waters of the northern (Div. 3L) and southwestern (Div. 3O) Grand Bank in fall. In addition, there were clear differences in the distribution of juvenile and adult catch rates in shallow waters of the bank in fall; as high juvenile catch rates were observed over the northern part of the bank (Div. 3L) and those for adults found in southern areas (Div. 3NO). Moreover, high juvenile catch rates were observed in northern areas in the fall; notably in the Hopedale Channel (Div. 2H). However, adult fish were mostly absent in tows north of Hawke Channel (Div. 2J).

Distribution of catch (spring and fall time series) in relation to depth showed that *A. radiata* tended to be found in deeper and broader water layers (200-600 m) in Div. 2HJ3KLMN, but in shallower and narrower layers (50-300 m) in Div. 3OPs, and were infrequently recorded in tows below 1000 m (Fig. 7). These patterns varied to some extent in a few areas over the years, along with changes in survey design, fishing gears, fish density and distribution patterns; whereas in other areas, few changes were detected. Mean catch rate (fall) peaked at depths ranging between 400-500 m in Div. 2H (1.2-5 kg/tow), Div. 2J (1.2-3.6 kg/tow), and Div. 3K (2.2-21 kg/tow); except in 1977-79 in Div. 2J and 2000-04 in Div. 3K, when catch peaked at depths of 300 m and 800 m, respectively (Fig. 8). Catch rates in these areas tended to increase with depth (>800 m) starting in the mid-1990s; due partially to the inclusion of deeper sampling strata, which occurred after 1993. Similarly, catch rates tended to peak at depth ranges of 400-500 m (spring and fall) in Div. 3L (8.2-58.1 kg/tow), and Div. 3N (13.5-149.8 kg/tow); except in Div. 3L in 1985-89 (fall), when the catch rate peaked at 600 m (366.3 kg/tow; highest estimate for both spring and fall series), as well as in Div. 3N in 1977-79 (fall), when the catch rate peaked at 200 m (138.2 kg/tow). In Div. 3M (fall), catch rate also peaked between 400-500 m, but values were consistently lower when compared to most areas of the Grand Bank (1.6-4.2 kg/tow). In Div. 3O (spring and fall) and Subdiv. 3Ps (spring), catch rate peaked in shallower waters when compared to the remaining areas (100-200 m in Div. 3O; 200-300 m in Subdiv. 3Ps), and varied little throughout the time series (14.2-26.6 kg/tow); except in spring in 1990-95 and 2000-04 in Div. 3O (33.5-44.3 kg/tow), and Subdiv. 3Ps (43.1-53.4 kg/tow).

Distribution of mean catch rate (spring and fall) in relation to temperature at tow depth indicated that *A. radiata* were distributed in waters varying from -1.1 to 7.1 ^{o}C; but tended to be found in preferential temperature ranges, which changed according to latitudinal and longitudinal clines (Fig. 9). In autumn, catch rate tended to peak within a narrow temperature band in northern and eastern areas (2-4 ^{o}C in Div. 2HJ3N; 3-4 ^{o}C in Div. 3KLM); but distributed over a broader range of temperatures (1-6 ^{o}C) in Div. 3O, as well as in spring over the entire Grand Bank and adjacent areas (Div 3LNOPs). These distribution patterns were consistent through the years in all areas; regardless of gear type employed, fish density levels, and extent of distribution.

Area of occupancy

Area of occupancy for *A. radiata* peaked in all NAFO Divisions prior to 1983, then declined steadily through the mid-1980s and mid-1990s (Engel trawl), and fluctuated without trend from the late 1990s onwards (Campelen trawl; Fig. 10). For Div. 2J3K in autumn, area occupied reached 82 % in 1980 and a minimum of 57 % in 1994; then varied between 61-73 % until the most recent assessment in 2009. Area occupied in spring by *A. radiata* in Div. 3LNO declined from 92 % in 1981 to 45 % in 1995, and then varied between 39-60 % during the last decade; whereas in Subdiv. 3Ps, *A. radiata* occupied 92 % of the surveyed area in 1972, but only 51 % by 1994, and fluctuated between 39-60 % in 1996-2010.

SIZE COMPOSITION AND ABUNDANCE INDICES

Gear catchability

Catchability of *A. radiata* by bottom trawls has been considered low; given the bottom-dwelling nature of this species. Walsh (1992) conducted escapement experiments for *A. radiata* and three other groundfish species on the Grand Bank, using an Engel bottom trawl. It was noted that escapement from the trawl was high for almost all sizes of skates. Maximum catching efficiency for *A. radiata* longer than 35 cm (TL) was about 40 % (typically 80 % or more for large sizes of the other three species). For all species tested, the Engel trawl appeared to be the least effective in capturing *A. radiata*. Skates of all sizes were observed to escape under the trawl's footrope.

Similar studies have not been conducted for the Campelen trawl. However, a sudden increase in biomass estimation in both spring and fall research surveys (Simpson and Kulka 2005) after the change in trawl gear in 1995-96, coupled with a very similar average size and frequency composition of skate captured (comparing the first two Campelen years with the last two Engel years), indicated that the Campelen trawl is more efficient than the Engel trawl in capturing skates of all sizes. Therefore, abundance estimations for *A. radiata* of all sizes from Canadian bottom trawl surveys must be viewed as minimum values.

Size

Length frequencies (TL) are presented for 1996-2009 (spring surveys) and 1996-2007 (fall surveys), and for the combined Div. 3LNOPs and Div. 3LNO, respectively. In spring, the length distribution for survey catches ranged between 5-105 cm (Fig. 11), and between 10-102 cm for the fall survey catches (Fig. 12). The mean length ranged between 38-50 cm in spring and 36-50 cm in fall, and mean length tended to increase over time in both cases: from 36-38 cm during the mid-1990s to 45-50 cm during the late 2000s (Table 2). Length frequencies were typically tri-modal; with modes reflecting the contribution of different cohorts/maturity stages to the survey catch. In spring, the dominant modal length (mode 1) in all years was comprised of juvenile fish (14-16 cm); except in 1999 (mode 1=40 cm). A second modal length, which included cohorts of predominantly immature fish, was observed until 2000 (32-40 cm) and adult fish during the last decade (46-69 cm). A third modal group included only adult fish through the time series (67-78 cm). In fall, the dominant mode reflected the prevalence of immature (36-

42 cm) and adult fish (46-62 cm) in the survey catch in half of the cases; whereas juvenile fish (14-18 cm) predominated in the other half. The second and third modal lengths were comprised in all years of juvenile/ immature (<40 cm) and adult fish (68-80 cm), respectively; except in 2004 (mode 2=55 cm) and 2006 (mode 2=59 cm).

Inter-annual variability in mean weight show a consistently declining trend in all Divisions from the 1970s to mid-1990s (Yankee and Engel time series), followed by an increasing trend in more recent periods (Campelen trawl time series; Fig. 13). Mean weight of *A. radiata* captured during spring surveys in Div. 3LNOPs declined from approximately 2.5 kg in the early 1970s to 0.8 kg in 1994, and since then increased through most years; peaking at 2.1 kg in 2007. Overall, the fall trend and mean values were very similar; despite Subdiv. 3Ps not being surveyed during the period. Similarly, the fall trend in Div 2J3K show that mean weight declined from approximately 1 kg in the late 1970s-early 1980s to 0.3 kg in 1995 (the lowest estimation in all time series), and then increased through the mid-1990s and peaked at 0.9 kg in 2007 before declining in 2009.

Catch rates and abundance estimation

Mean catch rates for spring surveys indicated that the highest densities of *A. radiata* were consistently observed at the southern Grand Bank and adjacent areas (Div. 3NOPs) throughout the time series (Fig. 14). Catch rates displayed mostly stable trends in Div. 3OPs (15-20 kg/tow; 10-15 fish/tow); regardless of changes in fishing gear. Similarly, catch rates varied little during the 1970s and 1980s in Div. 3L (10-17 kg/tow; 6-10 fish/tow) and Div. 3N (18-28 kg/tow; 9-13 fish/tow), but subsequent declines were observed in both areas until the mid-1990s; indicating that detected trends were not the result of sampling gear changes. However, an increasing trend in catch rates occurred since the beginning of the Campelen time series in Div. 3L and Div. 3N; although at different scales, as for the latter catch rates recovered to levels similar to those observed in the 1970s and 1980s (10-14 kg/tow; 6-8 fish/tow), but in the former, catch rates increased only marginally when compared to earlier periods (2-4 kg/tow; 1-2 fish/tow).

Mean catch rate for fall surveys confirmed that the highest densities of *A. radiata* were found over the Grand Bank (Fig. 15). More specifically, high catch rates were observed in Div. 3L during the 1980s (10-27 kg/tow; 11-17 fish/tow), and in Div. 3N (13-35 kg/tow; 8-20 fish/tow) and Div. 3O (9-30 kg/tow; 9-20 fish/tow) from the early 1990s onwards; once fall surveys included strata from those two Divisions. However, similar to spring estimates, catch rates in Div. 3L declined through the 1990s prior to the gear change, and remained much lower since then (1-5 kg/tow; 1-2 fish/tow); although some recovery has been detected more recently. Further north in Div. 2HJ3K, catch rates were generally low (1-4 kg/tow; 1-3 fish/tow), and varied with no clear trend. In Div. 2H, mean catch weight per tow was noted as consistently low (<3 kg/tow), but concerning numbers per tow, catch rates were amongst the highest (up to 37 fish/tow); especially since the Campelen trawl was introduced, indicating that *A. radiata* in this area are mostly small (young) fish.

Trends in spring survey abundance estimates for *A. radiata* in Div. 3LNOPs showed low inter-annual variability in most cases; but variability was more evident in some Divisions (Fig. 16). Abundance peaked at approximately 90 million fish/160,000 t in 1976, but ranged mostly between 40-50 million fish/60,000-80,000 t prior to 1992, and subsequently declined to 20 million fish/19,000 t in 1995: the lowest estimates in the time series (estimations lower in 1983, but only Subdiv. 3Ps surveyed at that time). Peak values in 1976 were the result of three anomalous high tow catches in Div. 3O (508, 428, and 243 kg/tow), and thus estimates for that year were likely biased. With the Campelen trawl, abundance estimates increased considerably to 50-70 million fish (1996-2010); whereas biomass increases were less evident in most cases, and compatible to those observed prior to the early 1990s (70,000-90,000 t). These discrepancies are likely related to the higher efficiency of the Campelen trawl in capturing skates from smaller size-groups.

Fall survey abundance estimates in Div. 3LNO showed a higher degree of inter-annual variability and were consistently higher when compared to spring estimates; notably in Div. 3N (number of fish and biomass) and Div. 3O (number of fish; Fig. 17). Between 85-90 % of fall abundance were found in Div. 3L in the 1980s, and in Div. 3NO since it began being surveyed in 1990. *A. radiata* abundance increased from 37-50 million fish/20,000-80,000 t in the 1980s to 50-100 million fish/80,000-120,000 t in the 1990s onward; peaking in 2008 (108 million fish/180,000 t). Abundance estimates in Div 2J3K comprised a small portion of the overall abundance; ranging between 1.4-6.3 million fish/500-4,600 t in Div 2J, and 3.5-14.4 million fish/1,700-12,000 t in Div 3K.

In spring prior to the mid-1990s, partitioning of *A. radiata* abundance (Div. 3LNOPs) by sex and maturity stage indicated nearly a 1:1 ratio between males and females for both immature and mature components of the population; but with the Campelen trawl, proportion of mature males increased between 20-50 % in relation to mature females; whereas for immature fish, the ratio tended to remain near 1:1 (Fig. 18). In fall for Div. 3LNO, a higher inter-annual variability in the sex ratio of mature fish was evident throughout the time series; with a prevalence of mature females (10-50 %) until the late 1990s and mature males thereafter. However, sex ratio for immature fish tended to fluctuate around ± 20 % throughout the time series. In Div. 2J3K, proportion of mature males ranged between 2 to 2.5:1 in relation to mature females during most years, and reached 6:1 in 2005, while the proportion of males to females among immature fish oscillated mostly between ± 25 %.

Ratio of the number of young-of-the-year (both sexes) and mature females in the previous year (assumed to be an indicator of recruitment) showed considerable inter-annual variability in *A. radiata* recruitment on the Grand Bank and adjacent areas (Div. 3LNOPs; Fig. 19). The index was high in 1996, 1997, and 2009 (1.6-2.4 recruits per spawner), suggesting good recruitment years; then declined to 0.55 in 1998 and remained < 1 during most of the last decade.

Central and Arctic Region

Survey catches of *A. radiata* occurred mostly off of the east and south coast of Baffin Island, between 68-70^{o}N (NAFO Subarea 0A), and extended southwest into Ungava Bay (Subarea 0B) at depths ranging between 500-1500 m (Fig. 20). The frequency of occurrence of survey tows with *A. radiata* increased in the latter, but nearly all tows conducted in the Hudson Strait recorded no catch of these skates; likely indicating the western limit of *A. radiata* distribution in that area. Furthermore, the higher frequency of tows with *A. radiata* close to the boundary with SA 1 (Greenland waters) and Div. 2G (Newfoundland waters) may reflect an extension of stocks from one or both of these areas. Survey catch weight and number were relatively low in SA 0AB and SFA 2 and 3, when compared to survey catch on the Grand Bank. Total weights and numbers ranged between 3.6-538 kg and 5-10,200 fish (Table 3).

Other Surveys of Interest

Surveys conducted in Div. 3NO by EU-Spain detected an increase in *A. radiata* biomass from approximately 10,000-50,000 t in 1995-2000 (González-Troncoso et al. 2010). Subsequently, there has been a decline in biomass to nearly 20,000 t in this area of the NRA. EU-Spain surveys in Div. 3L were limited at this time for the purpose of providing long-term trends (Roman et al. 2010). Data from long-term annual surveys conducted by Russia and France are the property of their respective governments, and are not included in this review. Surveys conducted off west Greenland on an annual basis indicated that *A. radiata* increased in abundance during the 1990s; but has since declined to pre-increase levels (Nygaard and Jorgensen 2010).

COMMERCIAL FISHERIES REMOVALS

NL Region

Canadian reported annual landings of *A. radiata* from all NAFO Divisions inside Canada's 200-Mile Limit were negligible prior to 1994, averaged 2,840 t in 1994-2003, and then declined to 1,382 t in 2004-09, with most landings originating in Div. 3O (1,874 t in 1994-99, with a 3,505-t peak in 1997) and Subdiv. 3Ps (1,175 t in 1994-2009, with a 2,000-t peak in 1995; Fig. 21).

Commercial landings statistics for *A. radiata*, based on Fisheries Observers' at-sea skates speciated catch data prorated to total reported groundfish landings (ZIF) inside Canada's EEZ in 1985-2009, averaged 488 t annually for the period 1985-91, and 1,112 t in 1992-2009, with a peak of 2,241 t in 2002 (Fig. 22). Catches peaked at 411 t in Subarea 2 (1993), 179 t in Div. 3K (2006), and 237 t in Div. 3L (1991); but average landings in all three areas declined from 96-224 t (1985-early 1990s) to 13-29 t (mid 1990s-2009). In contrast, average landings in Div. 3LNO increased from 29-50 t (1985-mid 1990s) to 231-500 t (mid 1990s onwards); with peaks of 958 t in Div 3N (2002), 1,268 t in Div. 3O (1993), and 619 t in Subdiv. 3Ps (1995).

NAFO-reported statistics (1960-2009) indicated that the majority of unspeciated skate catch was from Div. 3N; averaging 3,975 t (1969-99), with peaks of 14,541 t in 1988 and 12,696 t in 1991, 11,432 t in 2000-04, and 4,306 t in 2005-09 (Fig. 23). Considerable catches were also reported in Div. 3L; averaging 2,965 t in 1985-2004, with a peak of 15,587 t in 1991, and 235 t in 2005-09. Unspeciated skate catches with unreported locations averaged 13,279 t in 1994-2006, with a peak of 18,774 t in 2004; then declined to 808 t in 2007-08. In 2007-09, total NAFO-reported skate catches in all areas averaged 7,833 t annually.

With respect to fishing gear types used by Canadian fishers in Canada's EEZ, bottom trawls comprised the primary gear used between 1994-97, averaging 2,193 t annually; followed by gillnets with an annual average of 1,009 t (1995-2003) and 449 t (2004-09); then longlines with average landings of 447 t (1995-2009; Fig. 24). In total, 93 % of *A. radiata* catch from bottom trawls in the NL Region were from fisheries directed at other demersal fish species (Atlantic Cod, Redfish, American Plaice, Witch Flounder, Yellowtail Flounder) in 1978-2009 (Table 4). The geographic distribution of catch rates from these fisheries showed relatively low values (<50 kg/hour) throughout the NL Region during the late 1970s and early 1980s (Fig. 25). Catch rates increased substantially (>150 kg/hour) from the mid 1980s to early 1990s across the Grand Bank (Div. 3LNO) and shelf slope along the Laurentian Channel (Subdiv. 3Ps), and to a lesser extent on the Northeast Newfoundland Shelf (Div. 3K). However, catch rates declined across the NL Region during most of the last two decades; except for a few areas of high rates observed mainly in shallow waters of the Grand Bank (Div. 3O), and along the Laurentian Channel. Catch rates for the bottom trawl fishery directed at skates (1994-2009) were generally much higher as compared to catch rates for other bottom trawl fisheries (Table 4). However, the former was concentrated over a very small area of the shelf slope (Div. 3O) and along the Laurentian Channel (Subdiv. 3Ps; Fig. 26), where *A. radiata* were consistently found highly aggregated over the years (Fig. 4).

Available Fisheries Observers' commercial length frequencies for *A. radiata* indicated that bottom trawls (305 mm codend mesh) in skate-directed fisheries in Subdiv. 3Ps (2007) caught specimens ranging between 34-94 cm (TL), with highest numbers observed between 67-79 cm; whereas longlines (2008) fishing in the same area caught individuals ranging between 44-90 cm, with a modal length of 79 cm (Fig. 27). Moreover, gillnets (305 mm mesh) in Monkfish fisheries in Div. 3O (2007-08) were observed to catch *A. radiata* ranging between 56-96 cm; with highest numbers observed between 73-83 cm. In comparison, gillnets of 152 mm mesh and shrimp trawls of 50 mm codend mesh in Div. 3K (2008) caught *A. radiata* of 36-81 cm (peaks between 39-64 cm) and 14-20 cm (mode at 16 cm), respectively. No Observer data on this species were available for crab pots.

Observers' at-sea discards data for *A. radiata*, prorated to total reported groundfish landings (ZIF) in Subarea 2 and Div. 3KLNOPs within Canada's EEZ (1985-2010), indicated that in 1985-93 discarding occurred primarily in Div. 3LP, with an average in each Division of 2,450 t annually; followed by Div. 3NO (1,300 t), Subarea 2 and Div. 3K (500 t; Fig. 28). Discard estimates were greatly reduced in 1994-2010, and observed mainly in Div. 3NOP (150 t); followed by Subarea 2 and Div. 3KL (60 t). Since 2006, discards in combined areas averaged 459 t annually.

Central and Arctic region

A. radiata has been reported as bycatch in the Greenland Halibut fishery (both trawl and fixed gear fleets), and the northern shrimp fishery. Fisheries Observer coverage in the Greenland Halibut fishery for SA 0A has been 100 % since it began (1999); but coverage for the SA 0B fishery has been quite variable (e.g., fixed gear fleets have had 0 % coverage in some years). Observer coverage in the northern shrimp fishery has been 100 % since 1985, and use of a Nordmore grate to exclude fish from the shrimp catch became mandatory in 1997. Therefore, reported bycatch does not represent total bycatch for the years and areas where Observer coverage was <100 %.

Distribution and depth range of tows with *A. radiata* in the Greenland Halibut and northern shrimp fisheries corresponded well with those from survey catches. In both commercial fisheries, bycatch of *A. radiata* occurred mainly off of the east and south coast of Baffin Island (SA 0AB), as well as close to the boundary of Div. 2G and northern Ungava Bay (shrimp fishery only; Fig. 29). Bycatch levels were very low when compared to more southern areas, ranging between 0.002-6.5 t annually in the Greenland Halibut fishery, and 0.5-46 t in the northern shrimp fishery (Table 5). Bycatch of *A. radiata* in the shrimp fishery peaked in 1994 at 46 t, declined to 8.5 t in 1997, and then continued to decline to less than 1 t in 2008 and 2009.

DISCUSSION

This study compiled and analyzed the most recent data available from research surveys and commercial fisheries, and strengthened the knowledge of several key aspects of *A. radiata* life history and fisheries in Newfoundland and Labrador waters. Results indicated that (i) while *A. radiata* was distributed throughout the region from the Laurentian Channel to Baffin Bay, the main stock component was consistently found on the Grand Bank (Div. 3LNO) over time; (ii) habitat associations have been driven in part by (warmer) temperature preferences, and depth distribution was likely related to the water mass thermal profile over the shelf; (iii) indices of relative abundance varied little over most of the spring and fall survey time series in Div. 3OPs, despite changes in sampling gear types and stratification scheme over the years, suggesting that stock abundance remained near a steady-state condition in those areas; (iv) considerable declines in *A. radiata* abundance and extent of distribution occurred in Div. 3LN during the early 1990s; and (v) some signs of stock recovery have been detected, as the indices of relative abundance tended to increase in most areas during the last decade.

Differences between Canadian spring and autumn stock abundance estimates in Div. 3LNO have been related to seasonal movements and changes in distribution patterns over the years (Kulka et al. 2006). In spring, *A. radiata* tended to be found highly aggregated in deeper waters along the shelf slope of the Grand Bank, near the boundaries of the surveyed area; whereas in autumn the fish tended to move to shallower waters and were found scattered over the bank; especially adult fish (Figs. 4-5). Accordingly, a portion of the stock was likely unavailable to bottom trawls in spring (e.g., fish distributed beyond the surveyed boundary or found in few sampling strata); whereas in autumn a larger proportion of the stock was distributed more evenly in shallow strata, which corresponds to an increased availability of fish to bottom trawls (i.e., proportion of the stock in the surveyed area). However, the fall survey does not include Subdiv. 3Ps, which contains a considerable portion of the stock.

Moreover, the decline in abundance (mid-1980s to mid-1990s) and simultaneous contraction in area occupied in Div. 3LN resulted in a reduction in movements by *A. radiata*; with the concentration of most adult fish biomass in southern areas of the Grand Bank (Div. 3O) and the Laurentian Channel (Subdv. 3Ps) - notably male *A. radiata* (Fig. 18). Detection of hyper-aggregations (fish density remains high at the center of distribution; while decreasing elsewhere) in the same areas in the late 1990s-early 2000s (Kulka et al. 2004*b*) provided further evidence suggesting density and perhaps sex-dependent changes in distribution and movement patterns. These seasonal and longer term changes likely contributed to unusually large inter-annual variability in survey indices of relative abundance (e.g., 1997-98 in fall; 2009-10 in spring), and underestimated actual abundance of *A. radiata* during stock decline; particularly spawning biomass. Therefore, catchability of survey trawls changed over the years, and is an important consideration for determining stock status, and in the management of the fishery (Kulka and Mowbray 1998; Kulka et al. 2006).

Concurrent with the decline in survey indices of abundance, commercial catches of *A. radiata* reported by NAFO in Div. 3LNO declined from an average of 18,000 t annually (1985-91) to 7,500 t in 1992-95, and since 2000 estimated catches have averaged 9,000 t; although catch over the last 5 years averaged 5,300 t (Simpson and Miri 2010). Of note, survey indices for the same areas have been mostly stable since 1996, and that increasing trends in abundance and area occupied occurred only in recent years (2002-08; Figs. 10, 16, and 17). These statistics suggested that fisheries removals is a potential factor influencing *A. radiata* population dynamics on the Grand Bank.

Notwithstanding, record levels of environmental variability occurred in the Northwest Atlantic Ocean in the 1980s and early 1990s (Rice 2002; Colbourne et al. 2010), which coincided with important changes in the Newfoundland and Labrador shelf ecosystem; notably the near-collapse of dominant demersal and pelagic fish species, and a shift to an ecosystem regulated by benthic invertebrates (Gomes et al. 1995; Carscadden et al. 2001; Worm and Myers 2003). Most declines in *A. radiata* abundance and area occupied during that period occurred in northern areas of the Grand Bank, where commercial fishing effort was low (historically and presently); but bottom water temperatures reached record low levels (Kulka et al. 2006; Colbourne et al. 2010). It suggested that cooler water temperature was another important factor contributing to stock decline. Consequently, it was difficult to assess the contribution of different factors (e.g., survey trawl catchability, fish size and gender, migrations, fisheries removals, water temperature) affecting recent trends and variability in *A. radiata* abundance estimates and distribution patterns in Newfoundland and Labrador waters.

Several important aspects of the life history and fisheries of *A. radiata* in the study area are partially known or remain lacking. These include individual and area-specific growth rates, survival rates, age structures of immature and adult components of the stock, reproductive potential, identification of reproductive units, as well as a relationship between the spawning population and recruits. Inadequate biological sampling and reporting of commercial skate catches (e.g., catch limited to unspeciated removals by weight; unreported bycatch in other groundfish fisheries; unreported discards at sea; misreporting catch species) are also mentioned by Kulka et al. (2006). These missing data are critical to performing a comprehensive assessment of stock status. Currently, there are several ongoing research initiatives by DFO-NL Region aimed at obtaining the information necessary to generate realistic analytical assessment models for *A. radiata.* However, despite limitations, information provided in this study should be helpful to COSEWIC in assessing and formulating appropriate conservation and management strategies for *A. radiata* in Newfoundland and Labrador waters in terms of risk of extinction.

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Table 1. List of bottom trawl research surveys conducted in the Newfoundland and Labrador Region (NAFO Division 2HJ3KLMNOPs) during the period 1971-2010. Various vessels and fishing gears were used over the years. Vessels: A.T. Cameron, Gadus Atlantica, Wilfred Templeman, Alfred Needler, Teleost. Gears: Yankee-41.5 otter trawl (brown), Engel-145 otter trawl (blue) and Campelen-1800 shrimp trawl (yellow). White cell: no survey was conducted in the area/season/year. Fall/winter surveys (*).

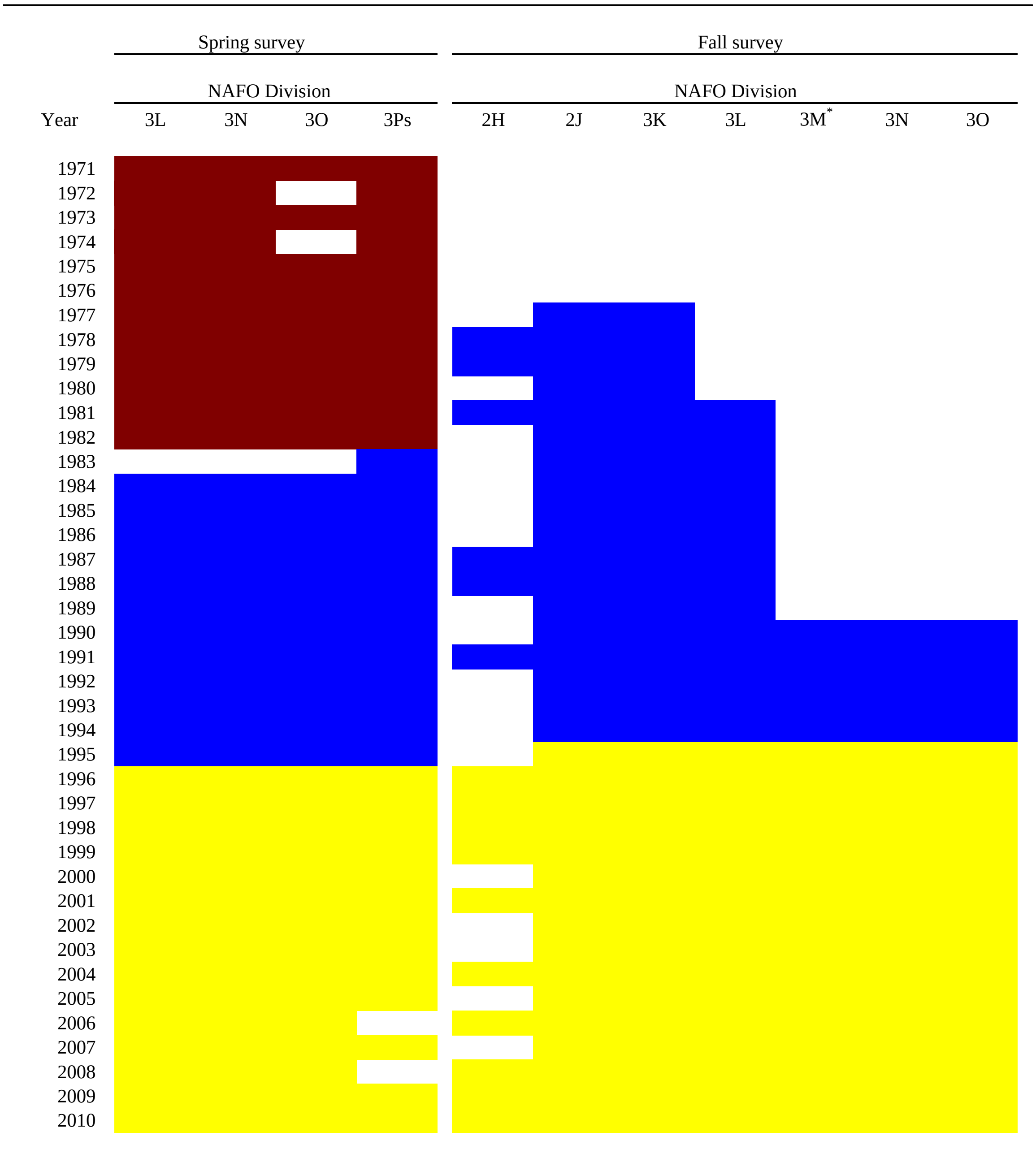

Table 2. Mean and mode estimation from available length frequency distributions (TL) for A. radiata caught during the spring (1996-2009) and fall (1996-2007) bottom trawl surveys in Division 3LNOPs.

	Spring Survey Div. 3LNOPs					Fall Survey Div. 3LNO				
		(cm)					(cm)			
Year	n	Mean	Mode 1	Mode 2	Mode 3	n	Mean	Mode 1	Mode 2	Mode 3
1996	4942	39	15	32	73	3659	36	15	23	68
1997	3107	38	15	34	75	2958	41	14	34	73
1998	3973	40	15	35	72	2066	44	18	38	72
1999	3528	45	40	17	70	1691	43	36	14	78
2000	3220	43	15	40	75	1880	43	14	39	75
2001	3278	49	15	46	71	1869	46	42	16	74
2002	2677	44	15	48	67	1655	49	46	16	80
2003	3815	47	15	51	74	1527	47	52	21	74
2004	2760	50	15	57	76	1561	44	18	55	74
2005	4891	42	16	55	72	1777	50	51	14	73
2006	1268	46	14	62	73	1570	50	17	59	75
2007	3637	48	15	66	73	2259	50	62	14	80
2008	6732	48	15	69	78					
2009	3429	45	14	63	75					

Table 3. Catch data for A. radiata in DFO surveys in SA 0AB, SFA 3 (Ungava Bay/Hudson Strait) and in NSRF surveys in SFA 2&3.

	SA 0A			SA 0B			SFA 3			SFA 2&3		
Year	No. tow	Catch weight (kg)	Catch No.	No. tows	Catch weight (kg)	Catch No.	No. tows	Catch weight (kg)	Catch No.	No. tows	Catch weight (kg)	Catch No.
1999	65	19.6	46									
2000				68	11.9	22						
2001	48	6.8	8	36	12.1	5						
2002												
2003												
2004	105	3.6	18									
2005										223	103.2	734
2006	164	26.5	66							223	115.3	740
2007							101	537.6	10200	237	182.7	937
2008	86	37.7	135							233	258.6	1245
2009							133	347.9	1288	250	221.7	1295

Table 4. Recorded catch and catch rate for A. radiata directed bottom trawl commercial fishery and bycatch from fisheries directed at Atlantic cod, redfish, American plaice, witch flounder and yellowtail flounder (combined bycatch) in the NL Region (1978-2009).

	Directed fishery			Bycatch		
Year	No. tow	Catch (t)	Cath rate (kg/hour)	No. tow	Catch (t)	Cath rate (kg/hour)
1978				509	65.2	46.9
1979				3808	175.5	17.8
1980				7321	408.8	23.2
1981				9679	658.6	27.2
1982				8028	504.5	27.2
1983				7799	768.1	38.6
1984				5197	532.4	40.6
1985				2473	265.9	540.9
1986				2999	251.7	379.8
1987				7382	433.3	287.1
1988				5942	755.7	755
1989				4088	548.4	501.5
1990				7693	613.6	319.1
1991				7876	677.3	345.3
1992				5504	727.0	454.9
1993				2802	547.3	683.4
1994	77	230.8	8004.6	575	14.5	68
1995	5	0.3	474	220	6.1	115.9
1996	33	62.2	4725.1	533	11.0	75.6
1997				360	17.8	273.4
1998	39	87.4	10970.1	1155	43.7	158
1999	18	25.4	4885.6	1200	43.4	151.8
2000				1348	66.9	177
2001	51	194.9	18555.5	2497	187.9	251.3
2002	8	0.7	308.2	3016	239.3	309.9
2003	10	8.9	4419.8	2880	300.0	451.6
2004	6	1.8	466.5	2389	164.9	318.5
2005	16	32.4	9889	2081	137.0	271.4
2006				380	34.3	289.8
2007	13	46.6	11936.4	797	76.3	412
2008		0.0		1268	95.1	294.6
2009	10	7.1	286.5	1296	79.4	22.8
Total		698 (7%)			9,451 (93%)	

Table 5. A. radiata bycatch in the northern shrimp fishery in NAFO SFA 0, 1, 2 and 3 since 1979, and in the Greenland halibut fishery in SA 0AB since 1992.

	Northern shrimp		Greenland halibut					
	Trawl		Trawl (single & double)		Gillnet		Longline	
Year	No. tow	Catch (t)	No. tow	Catch (t)	No. tow	Catch (t)	No. tow	Catch (t)
1979	158	6.32						
1980	511	14.20						
1981	4923	2.26						
1982	2203	0.56						
1983	1712	0.65						
1984	1251	3.55						
1985	1825	0						
1986	2015	7.76						
1987	1359	4.34						
1988	3416	6.68						
1989	7688	30.44						
1990	4679	21.06						
1991	6632	32.17						
1992	5307	41.70	176	0				
1993	3117	45.53	220	0				
1994	3917	46.08						
1995	1978	25.99	933	0.19	41	0	280	0
1996	4503	40.97	1068	3.1	60	0		
1997	3590	8.5	1333	1.43				
1998	2413	4.73	479	0.05	44	0.002		
1999	3451	5.52	541	4.51	76	0		
2000	3009	6.21	345	0.64	71	0	56	0
2001	3038	5.78	932	0	30	0		
2002	3535	3.84	755	0.003	71	0.21	897	0.01
2003	2901	2.81	1115	1.29			675	0
2004	3731	2.41	1258	4.91	10	0	297	0
2005	2037	2.58	1053	0.95	367	0.01		
2006	2151	4.14	863	0.79	1102	0.14		
2007	1802	4.38	1299	6.52	808	0.13		
2008	na	0.63	867	0.39	612	0.46		
2009	na	0.17						
Total		382 (93%)		25 (6%)		0.95 (< 1%)		0.01 (< 1%)

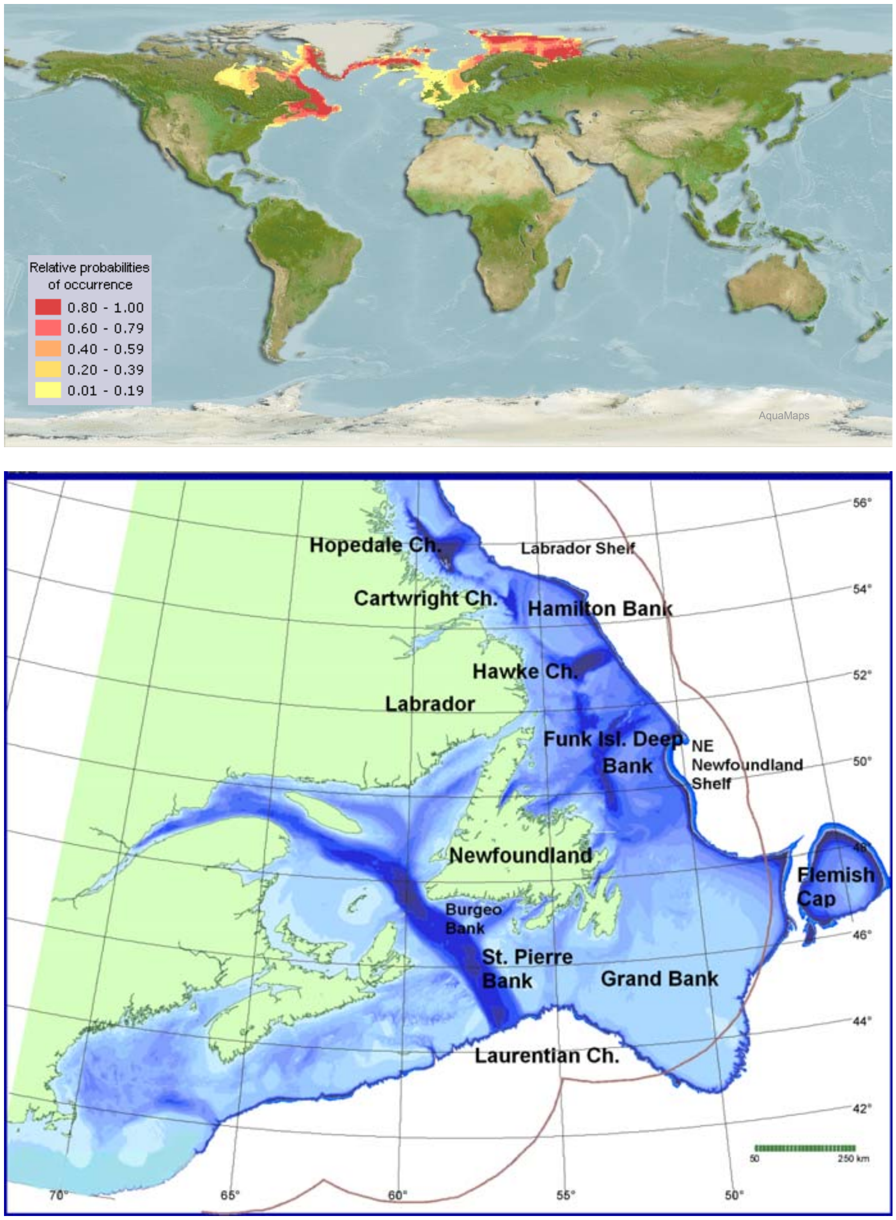

Figure 1. Upper panel: World map delineating the extent of the geographic distribution of A. radiata. Lower panel: Bathymetric map of the continental shelf off Eastern Canada and geographic features mentioned in the text. Depth range: <100 m (light blue) to >1000 m (dark blue). Canada's 200-mile limit (brown line).

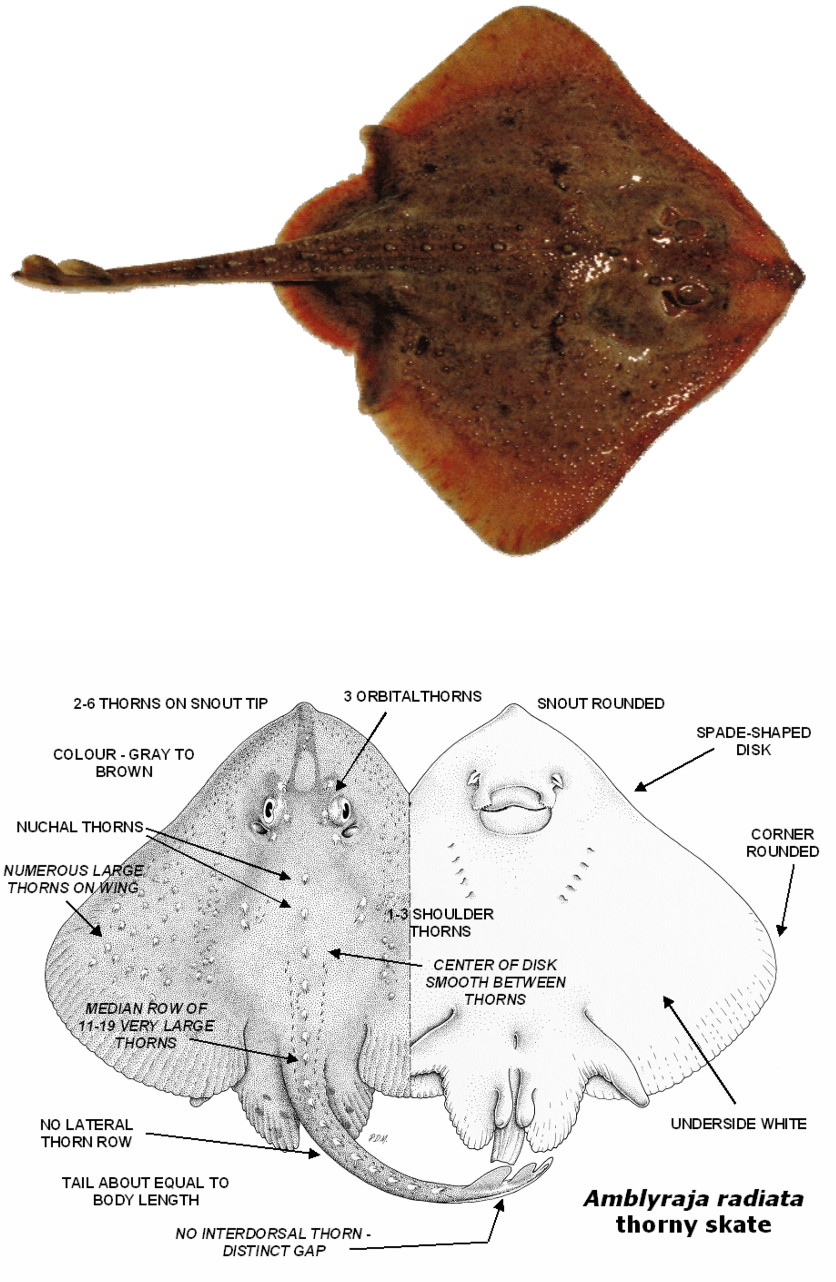

Figure 2. Upper panel: dorsal view of a female A. radiata from the Grand Bank. Lower panel: drawing highlighting morphometric attributes used for species identification (after Sulak et al. 2009).

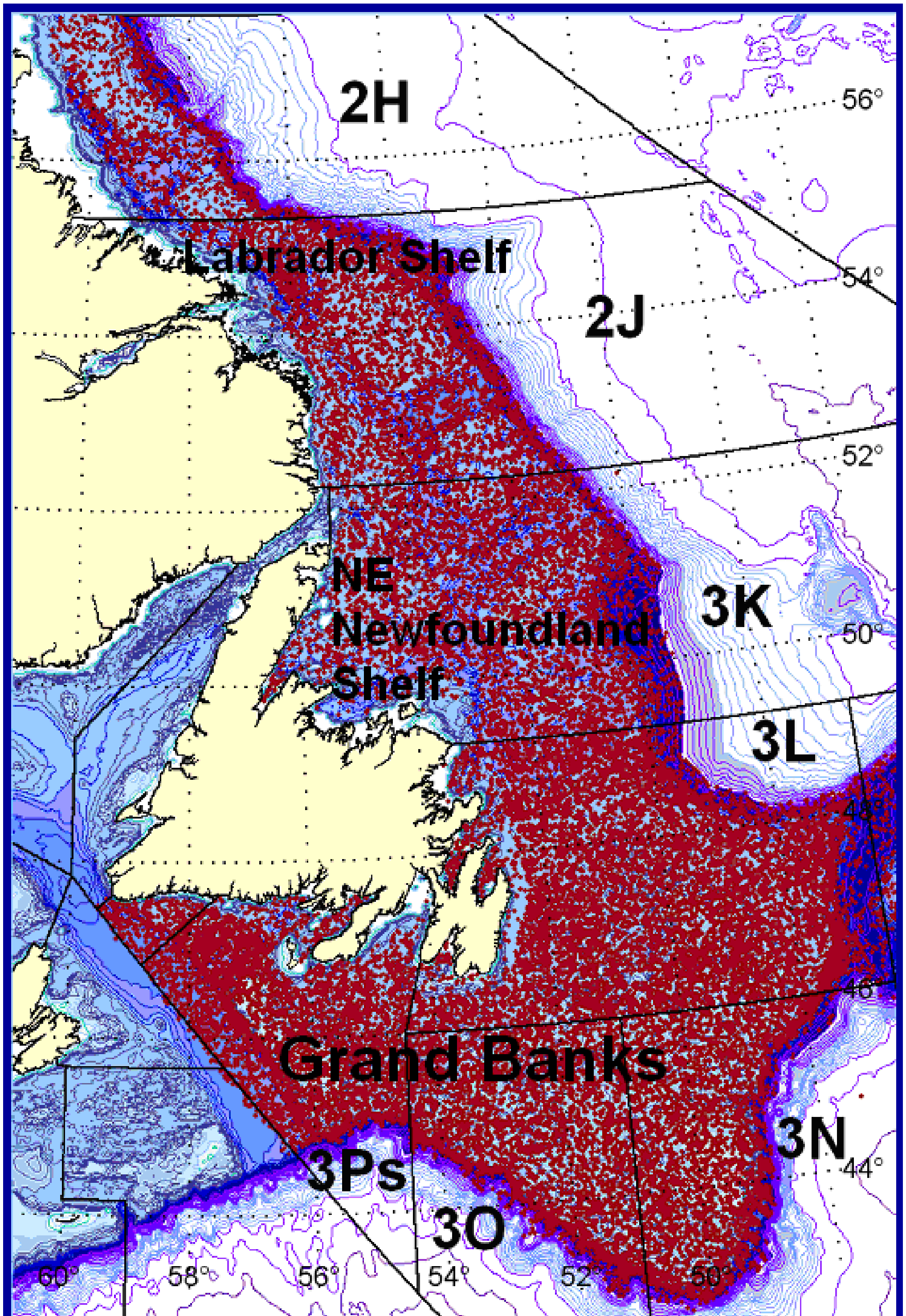

Figure 3. Distribution of fishing tows (red dots) conducted during spring and fall bottom trawl research surveys in NAFO Division 2HJ3KLMNOPs during the period 1971-2010 (all data combined). Solid black lines delineate NAFO Divisions. Fishing gear changed from Yankee to Engel in 1983 (spring survey) and from Engel to Campelen in 1995 (fall survey) and 1996 (spring survey).

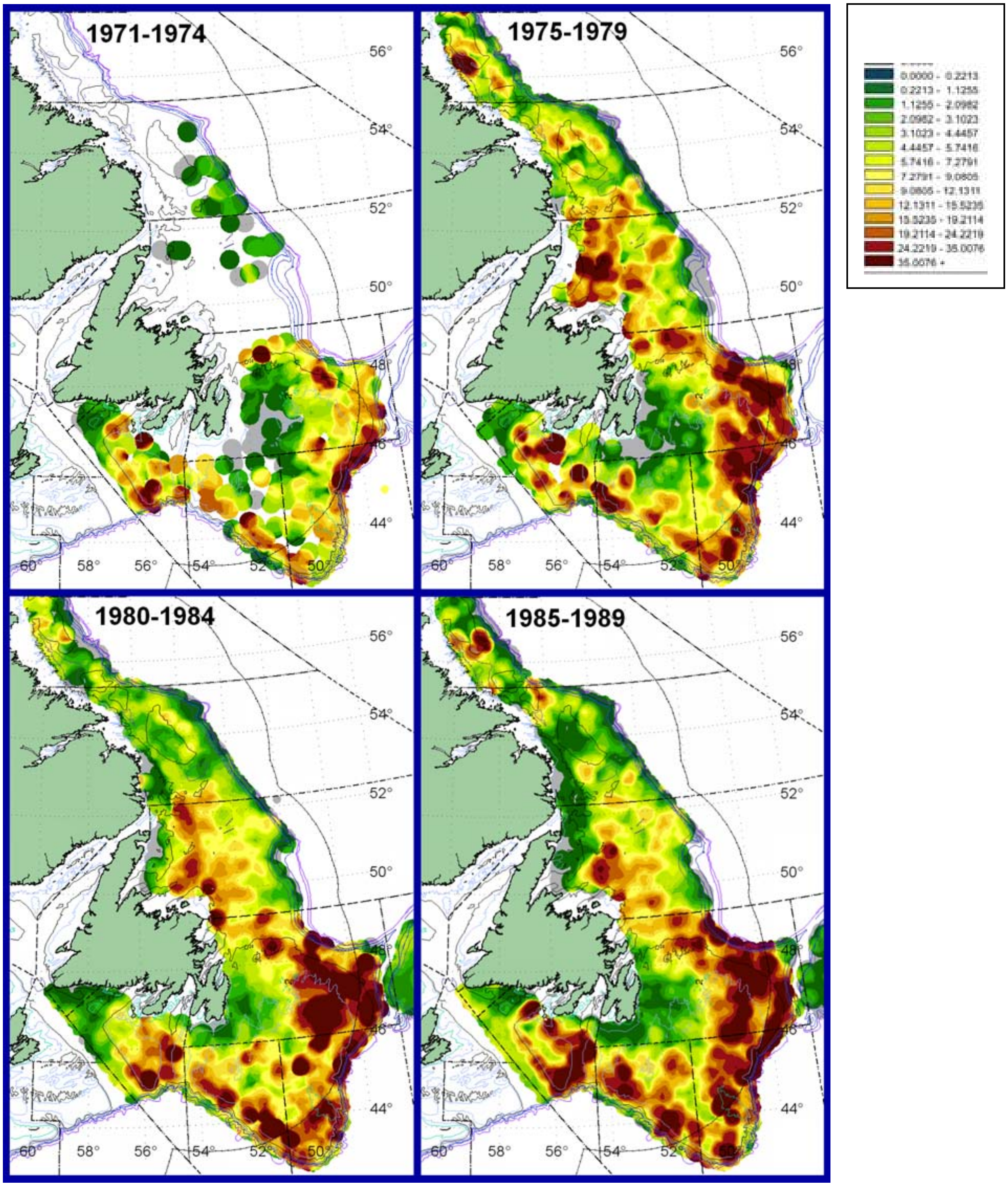

Figure 4. Distribution of A. radiata catch rate in the waters off Newfoundland and Labrador for combined spring and fall surveys by five year intervals. Grey denotes areas sampled but with no catches. Maps were produced using the surface modelling technique described in Kulka (1998).

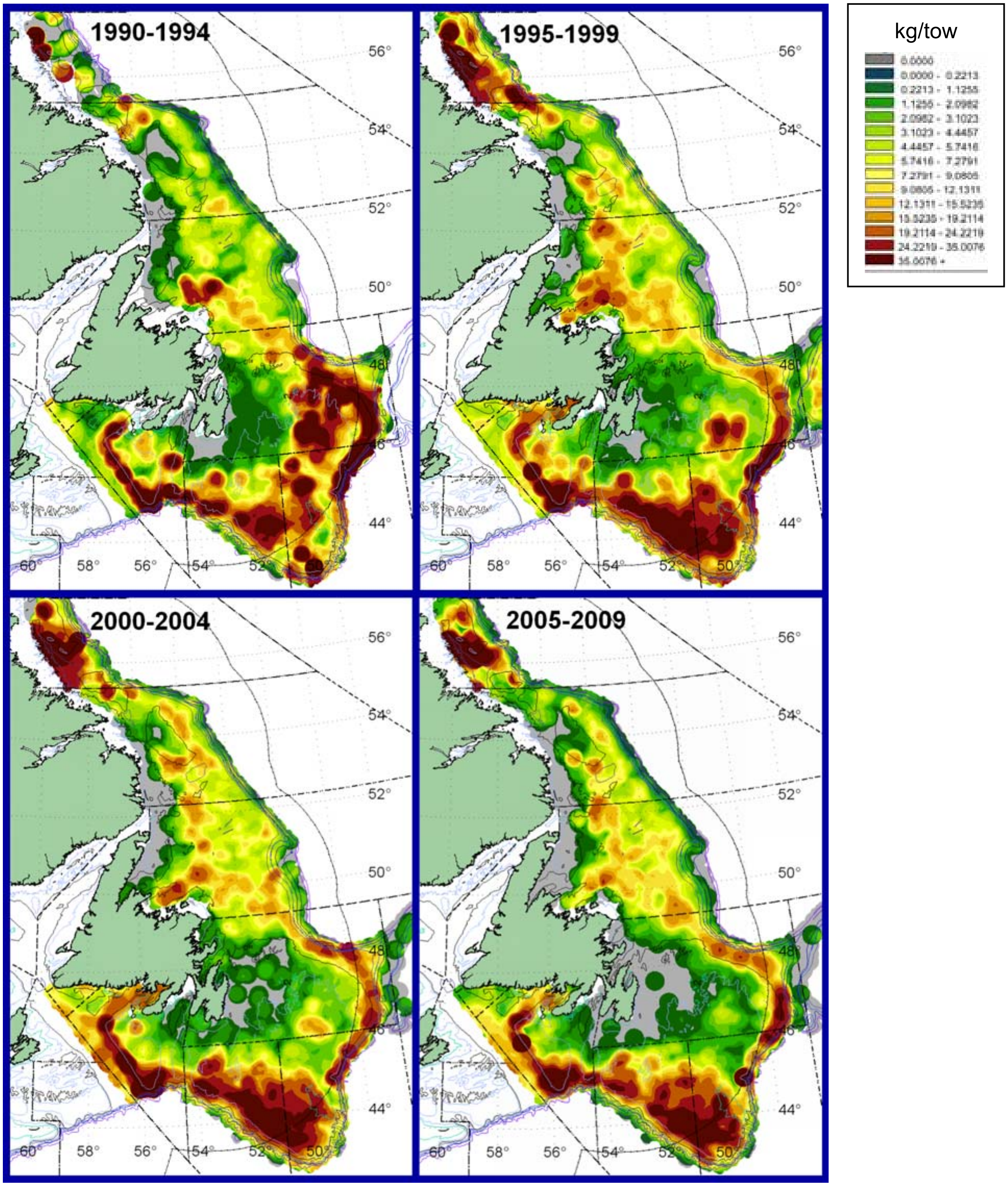

Figure 4 (cont'd.). Distribution of A. radiata catch rate in the waters off Newfoundland and Labrador for combined spring and fall surveys by five year intervals. Grey denotes areas sampled but with no catches. Maps were produced using the surface modelling technique described in Kulka (1998).

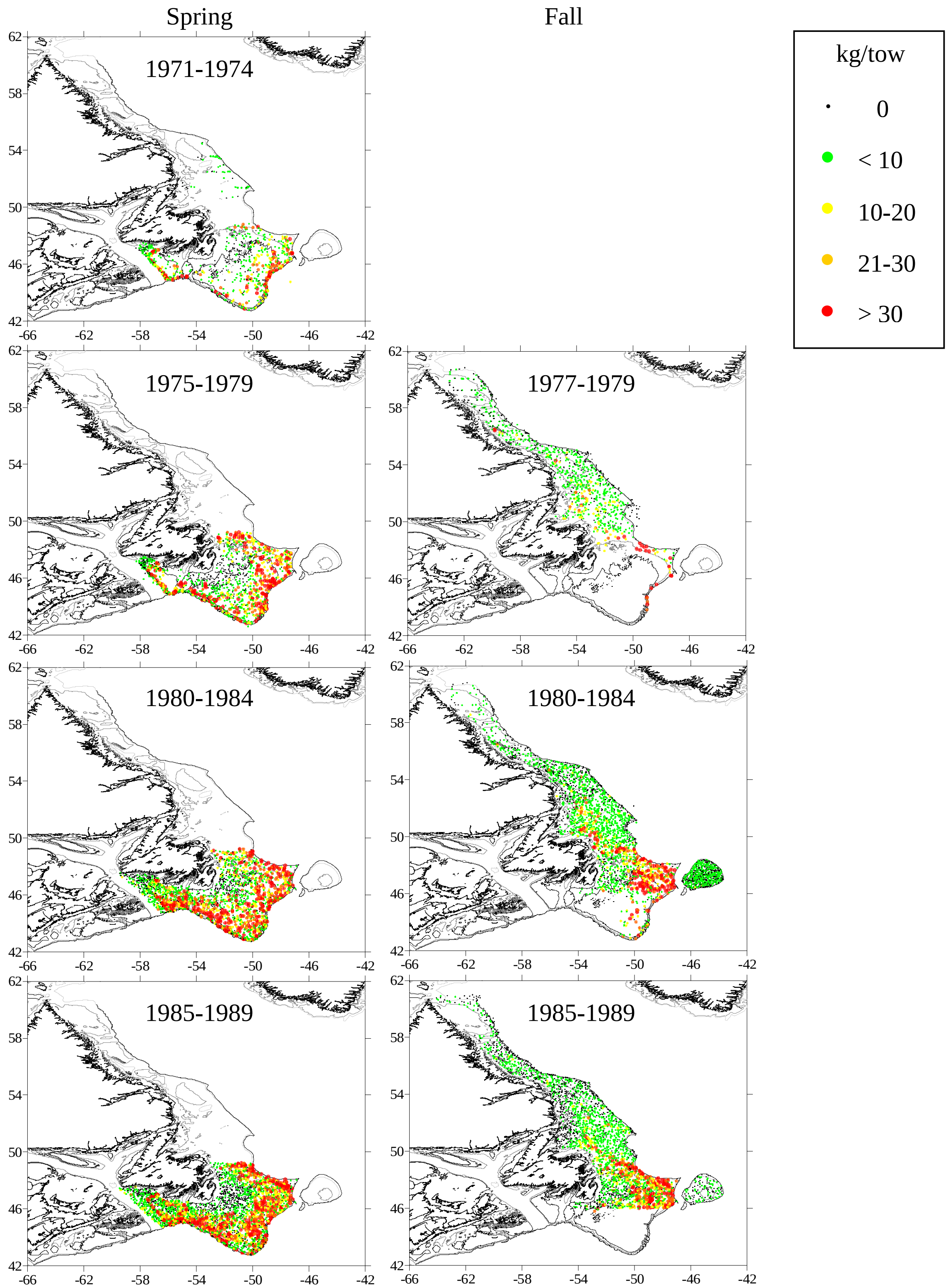

Figure 5. Geographic distribution of spring (left panels) and fall (right panels) bottom trawl research survey catch rate (kg/tow) for A. radiata in the NL Region.

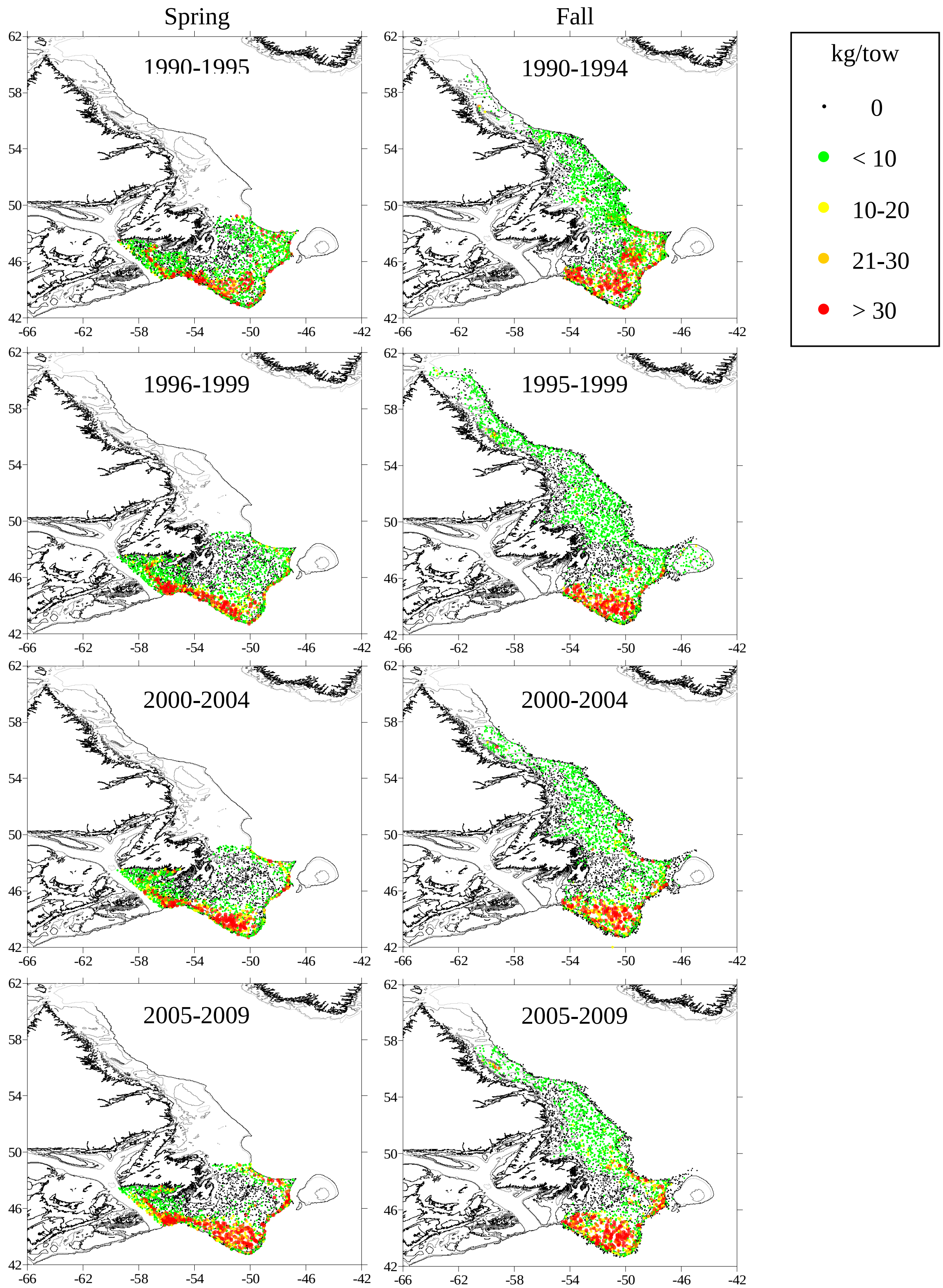

Figure 5 (cont'd.). Geographic distribution of spring (left panels) and fall (right panels) bottom trawl research survey catch rate (kg/tow) for A. radiata in the NL Region.

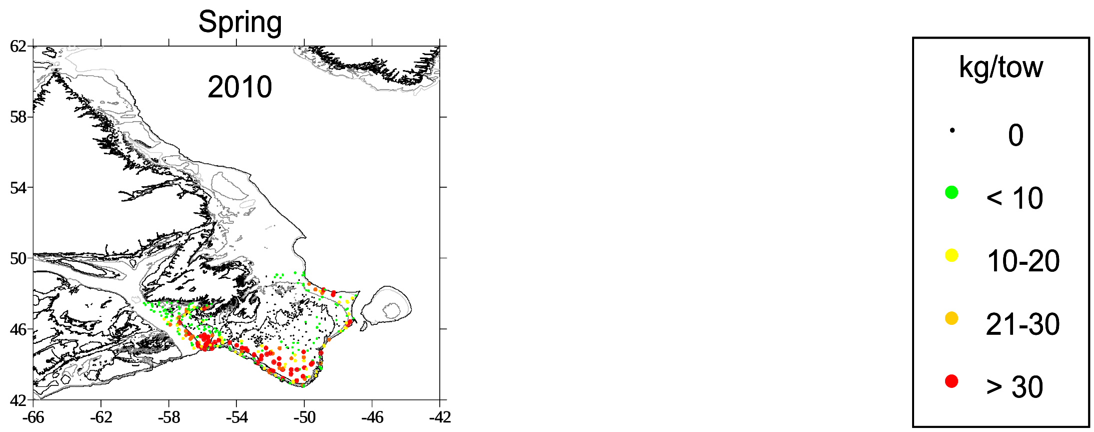

Figure 5 (cont'd.). Geographic distribution of spring bottom trawl research survey catch rate (kg/tow) for A. radiata in the NL Region.

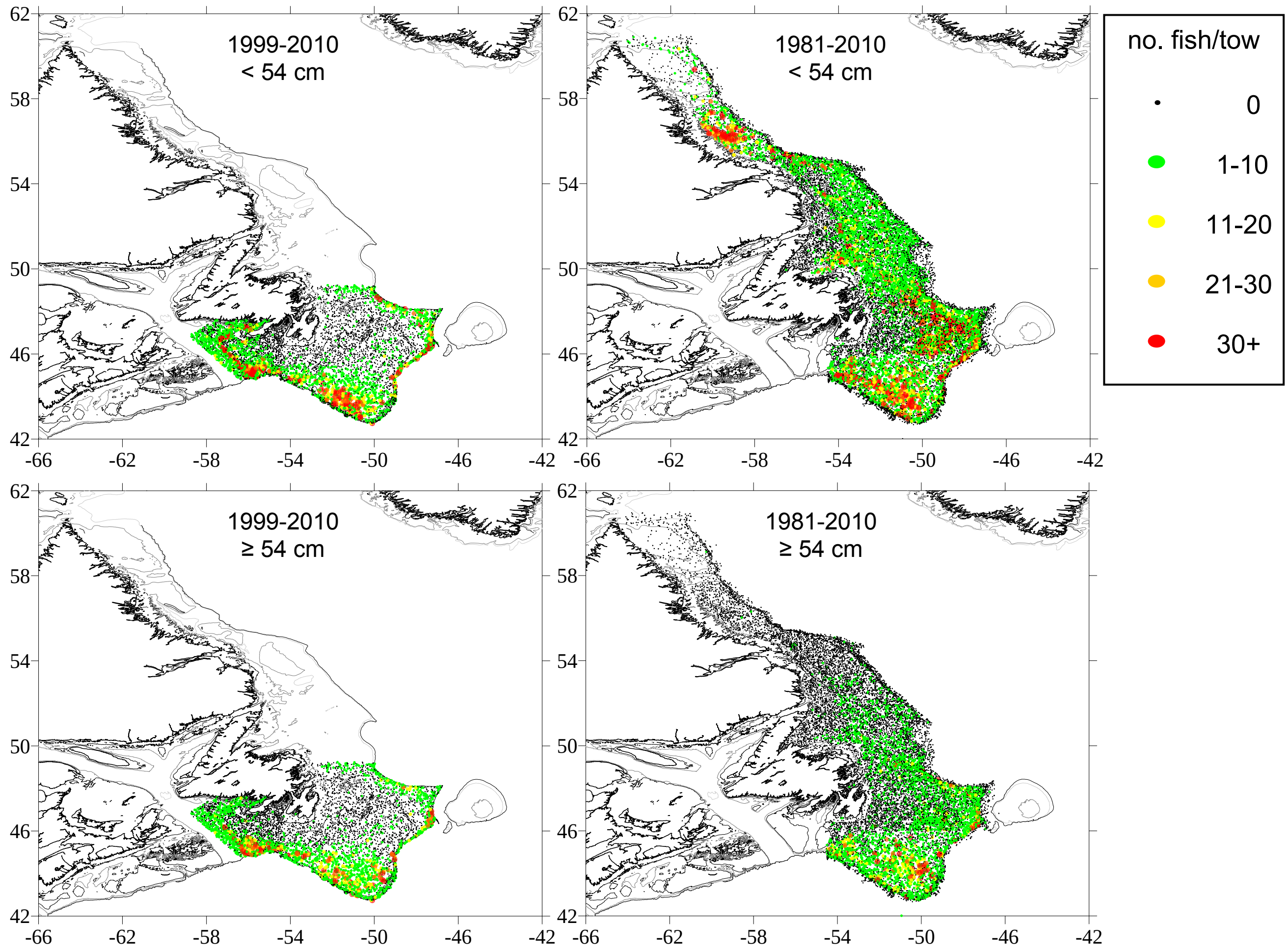

Figure 6. Geographic distribution of spring (left panels) and fall (right panels) bottom trawl research survey catch rate (no. fish/ tow) for juvenile (<54 cm) and adult (≥54 cm) A. radiata in the NL Region.

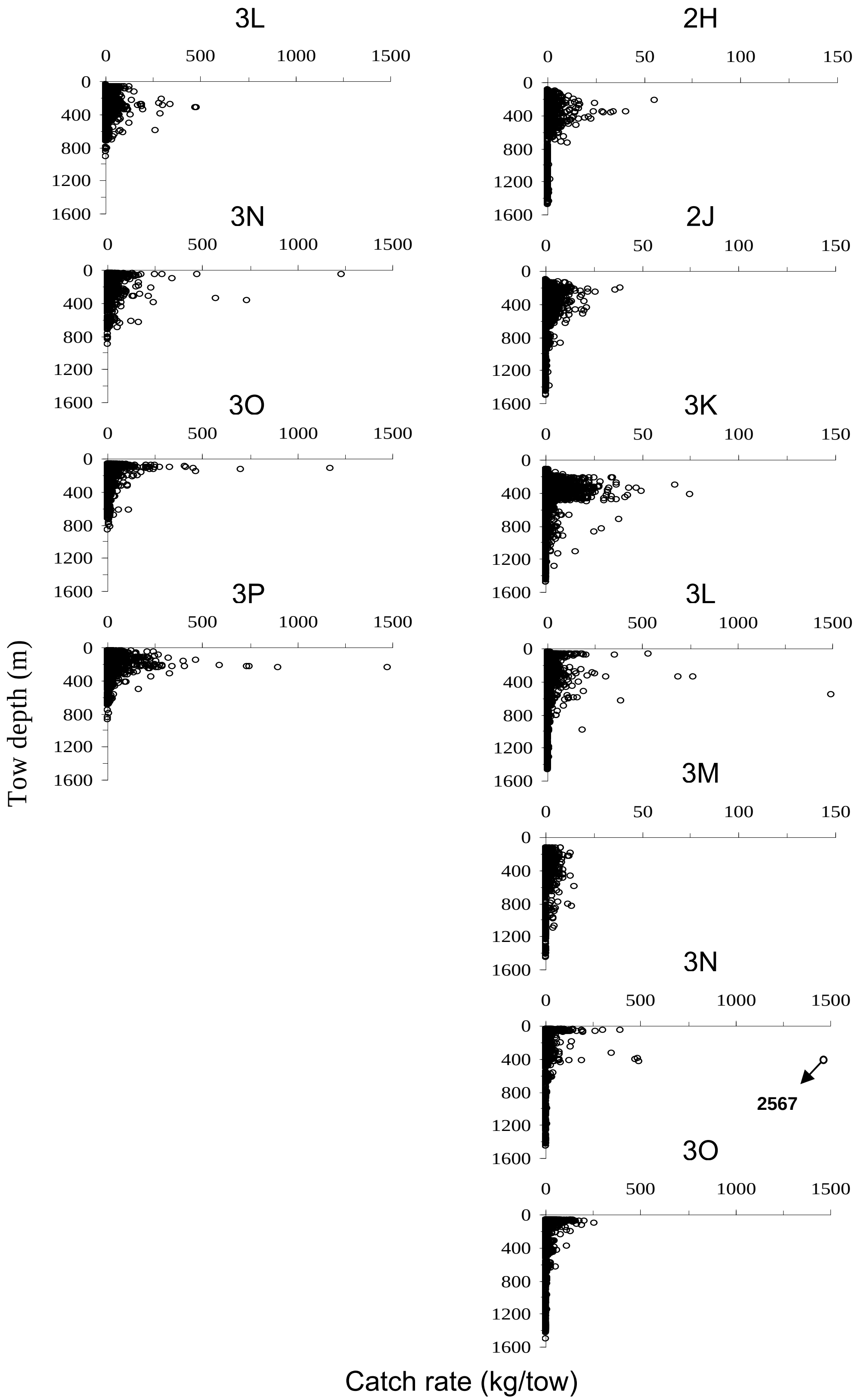

Figure 7. Distribution of spring (1971-2010) and fall (1977-2009) bottom trawl catch rate (kg/tow) for A. radiata in relation to depth in the NL Region (Division 2HJ3KLMNOPs). Left column (spring), right column (fall).

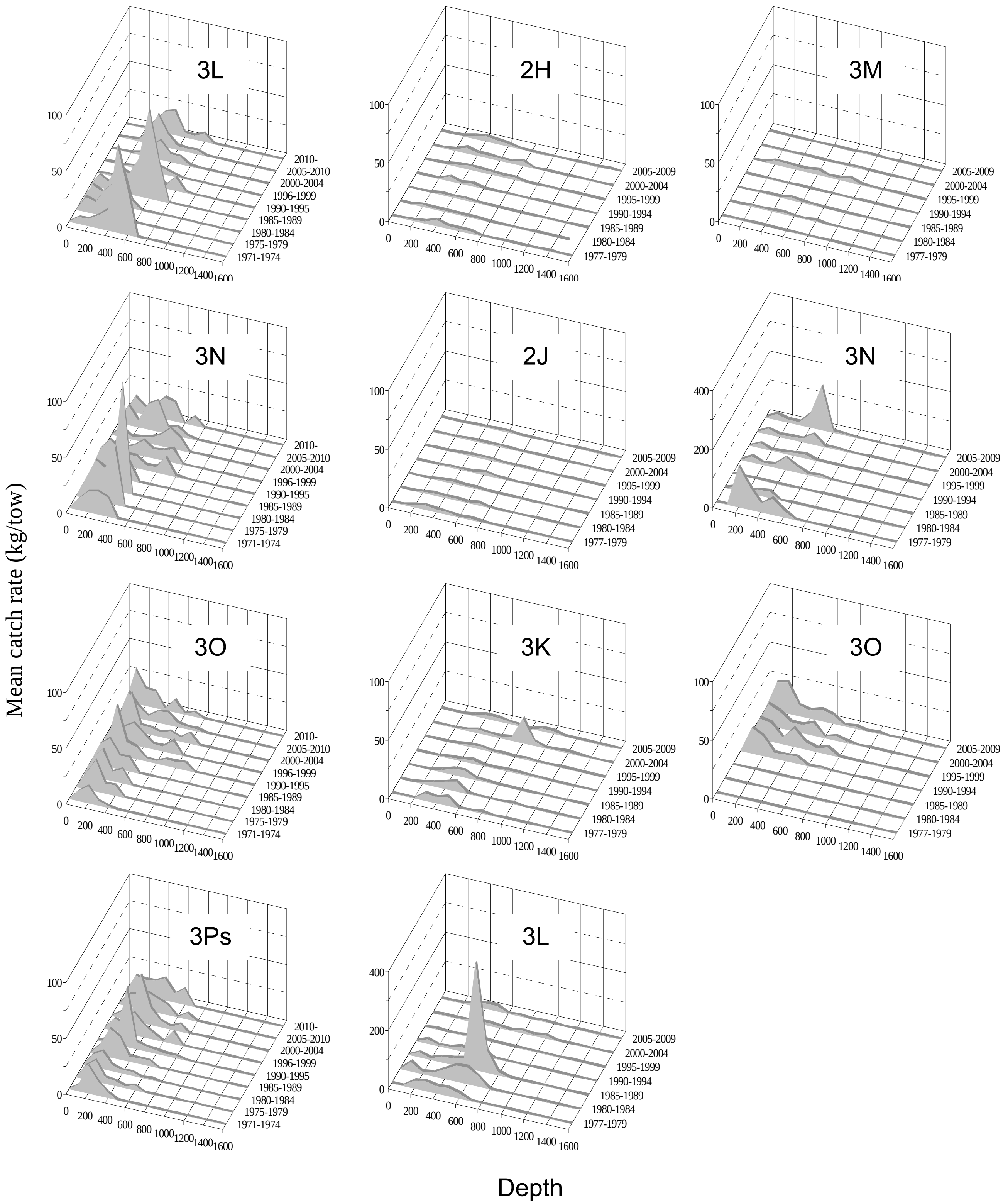

Figure 8. Distribution of A. radiata mean catch rate in relation to depth during the spring (1971-2010) and fall (1977-2009) bottom trawl research survey in the NL Region (Divsion 2HJ3KLMNOPs). Left column (spring), centre and right columns (fall).

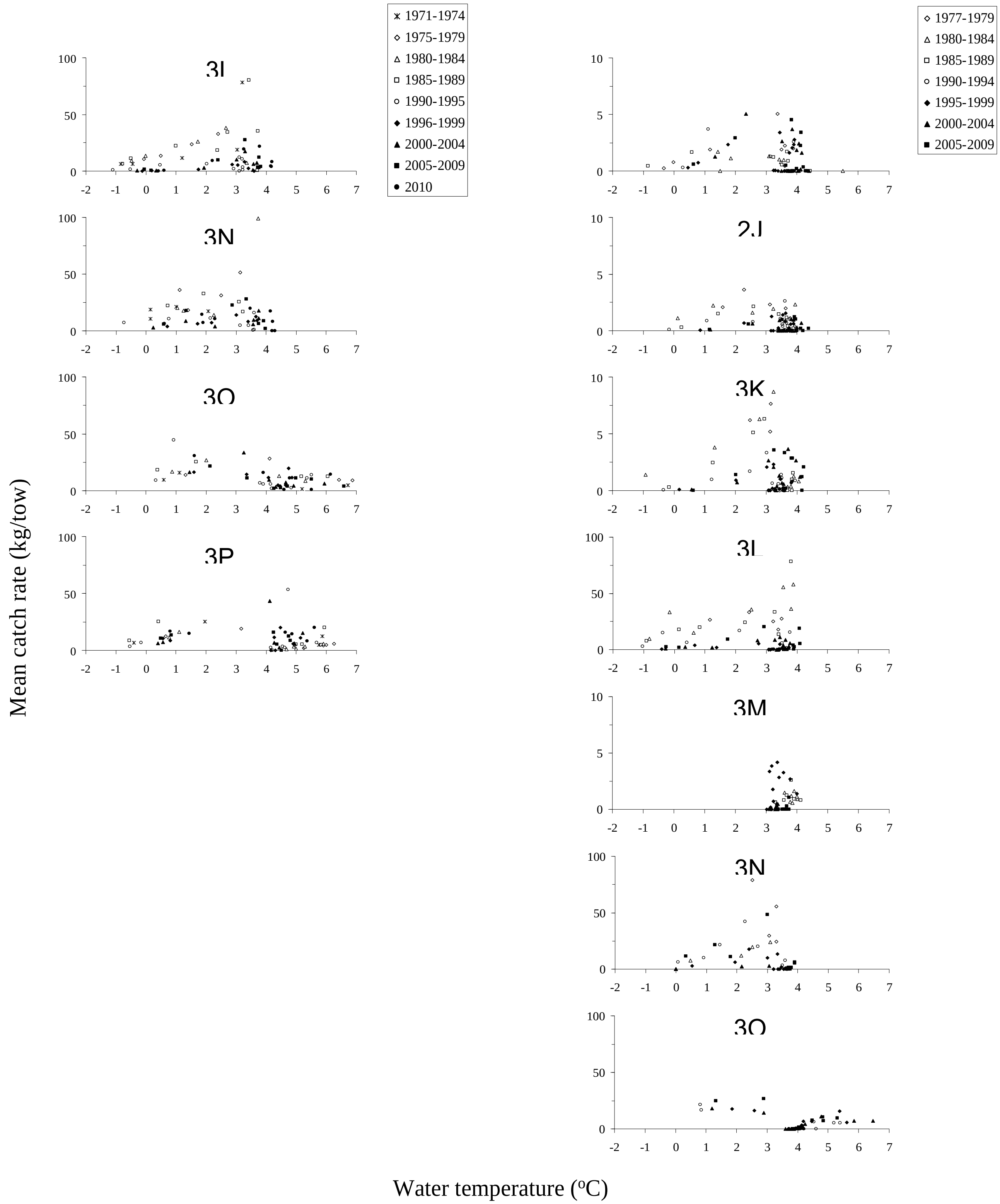

Figure 9. Distribution of A. radiata mean catch rate in relation to water temperature at tow depth during the spring (1971-2010) and fall (1977-2009) bottom trawl research survey, NL Region (Div. 2HJ3KLMNOPs). Left column (spring), right column (fall).

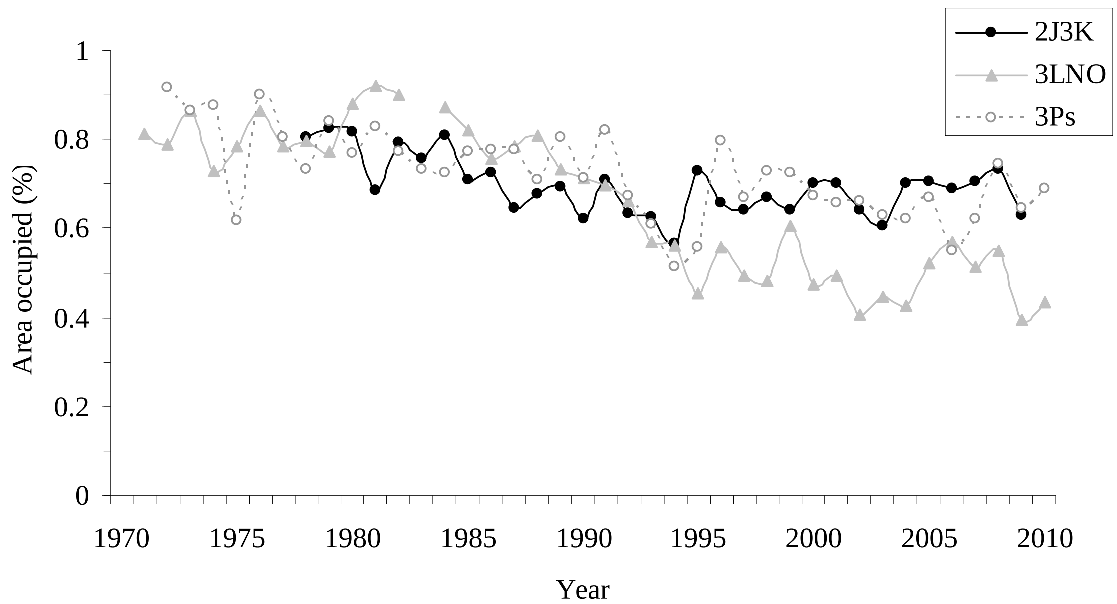

Figure 10. Area of occupancy for A. radiata in Division 2J3K during the fall (1978-2009) and in Divsion 3LNO and Division 3Ps during the spring (1971-2010).

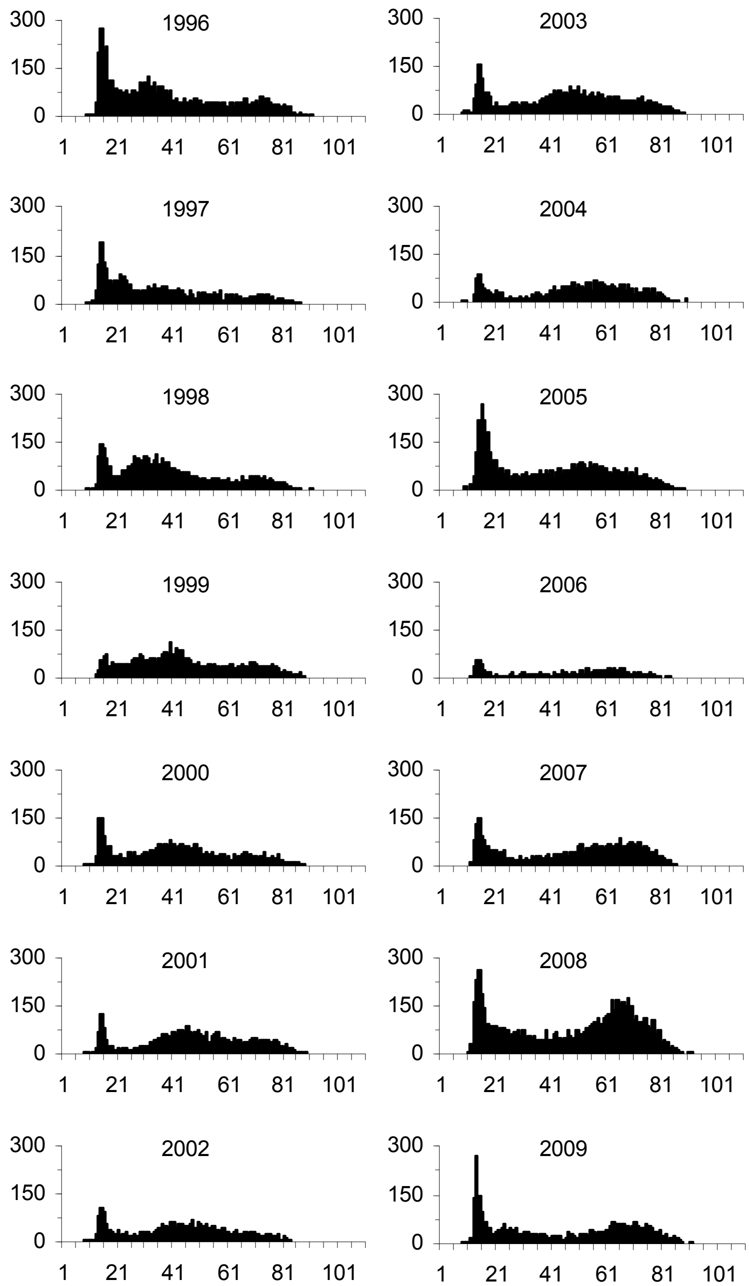

Figure 11. Length frequency distribution (TL) for A. radiata caught during the spring bottom trawl survey (1996-2009) in Division 3LNOPs. All tows were conducted using a Campelen trawl.

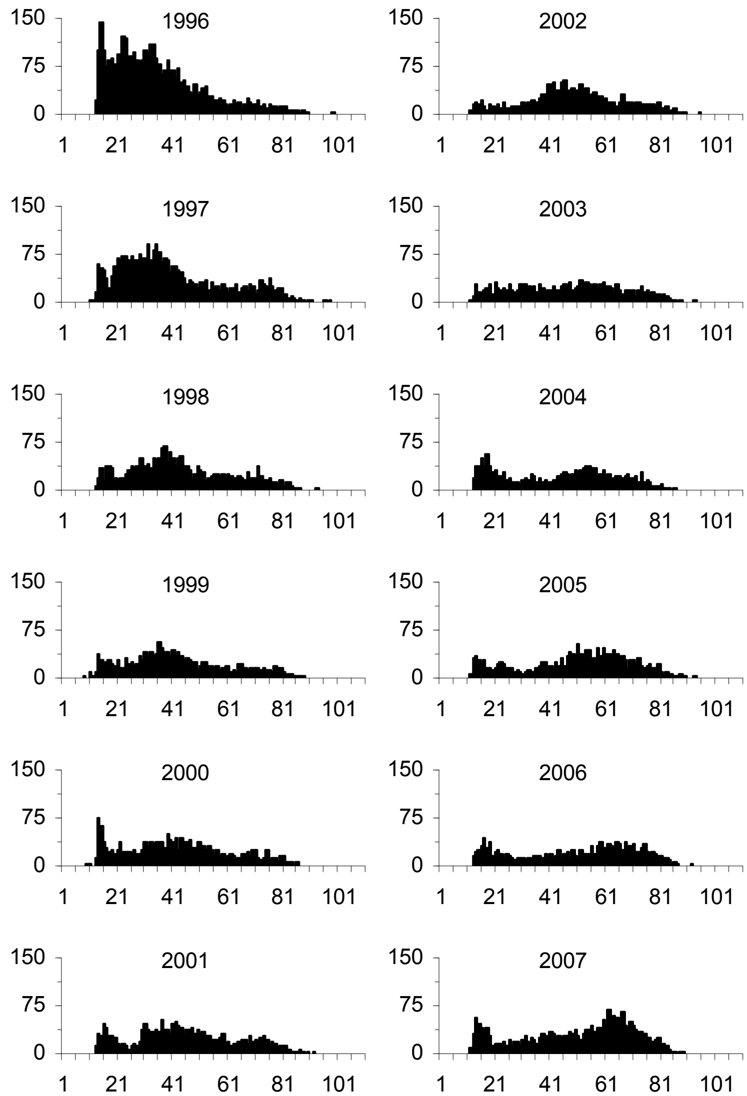

Figure 12. Length frequency distribution (TL) for A. radiata caught during the fall bottom trawl survey (1996-2007) in Division 3LNO. All tows were conducted using a Campelen trawl.

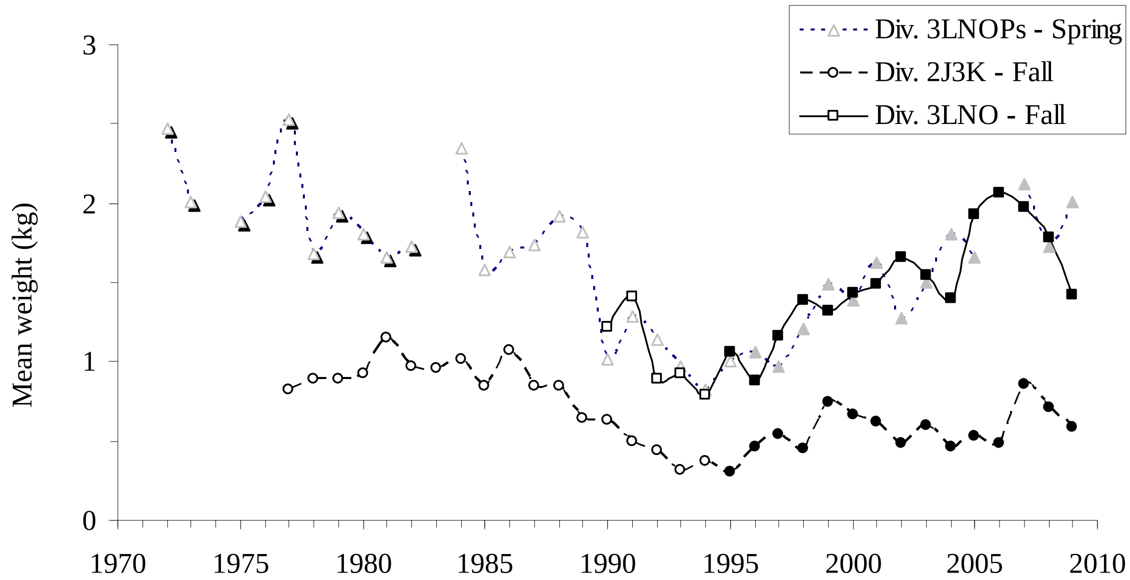

Figure 13. Mean weight of A. radiata caught during the spring (1971-2010) and fall (1977-2009) bottom trawl surveys in Division 2J3KLNOPs. For each survey, the mean weight was calculated as the ratio between the total catch weight and total catch number estimated using the STRAP routine. Survey fishing gear changed from Yankee (shadow marker) to Engel (open marker) in 1983 and from Engel to Campelen (closed marker) in 1995-96.

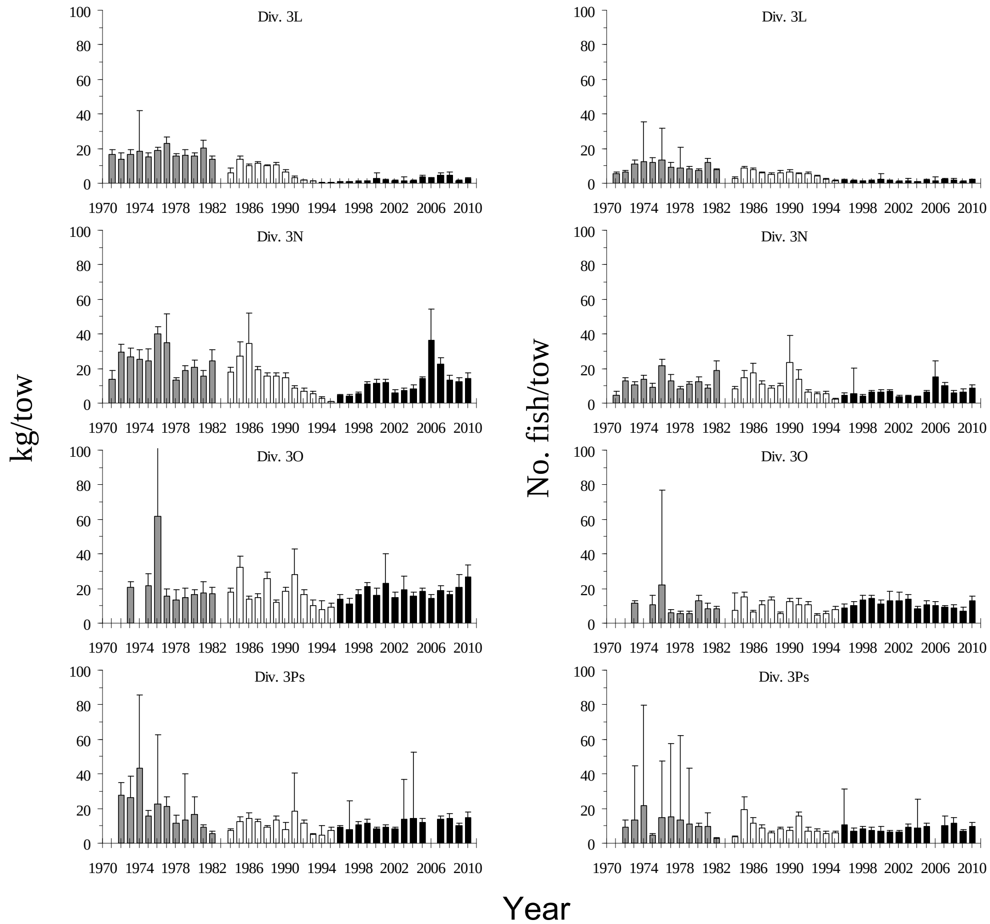

Figure 14. Spring bottom trawl survey standardised indices of relative abundance (1971-2010) for A. radiata in Division 3LNOPs. Left column: mean catch weight per tow. Right column: mean catch number per tow. T-bar = 1 SE. Survey fishing gear changed from Yankee (grey bars) to Engel (white bars) in 1983, and from Engel to Campelen (black bars) in 1996.

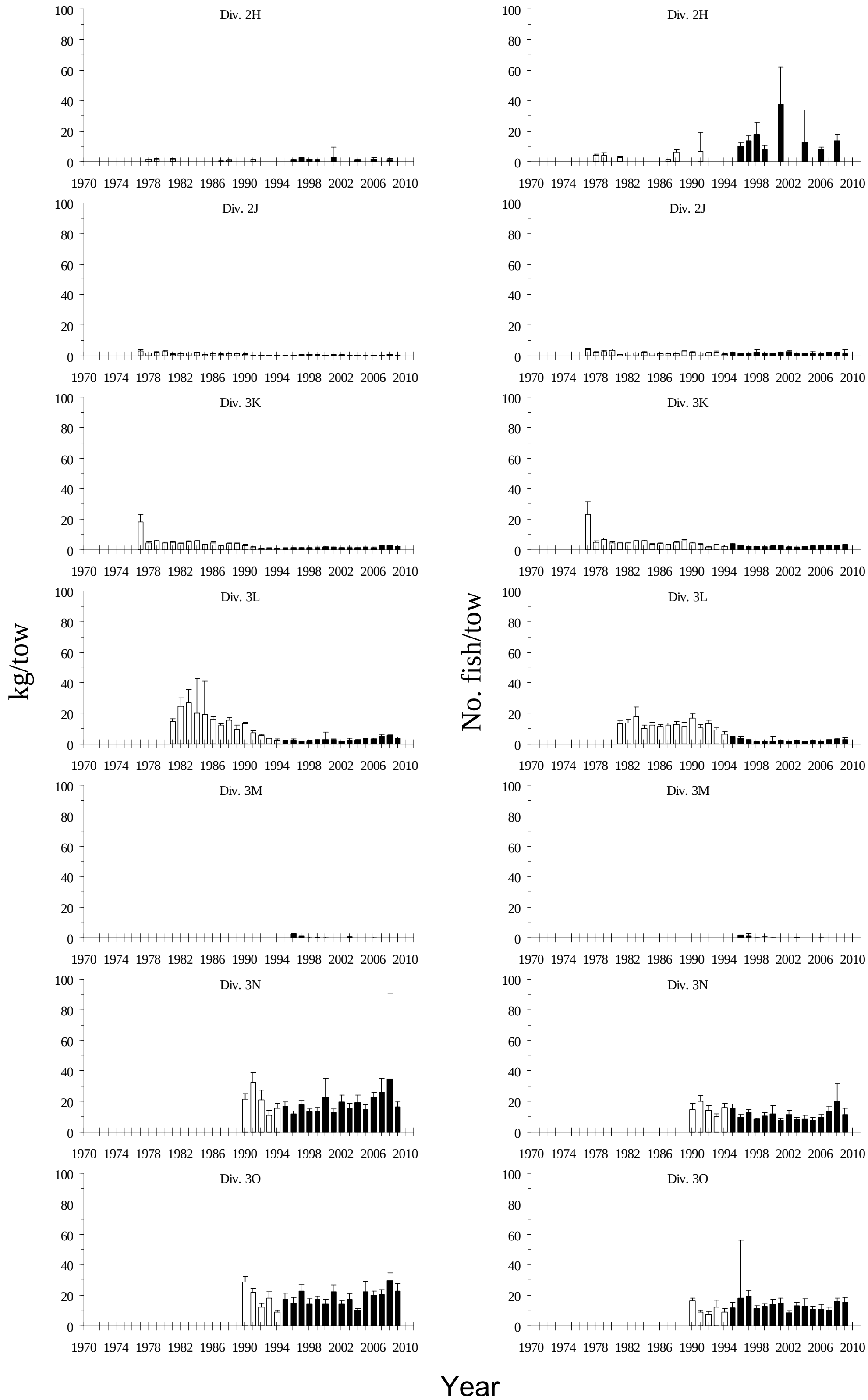

Figure 15. Fall bottom trawl survey standardised indices of relative abundance (1977-2009) for A. radiata in Division 2HJ3KLMNO. Left column: mean catch weight per tow. Right column: mean catch number per tow. T-bar = 1 SE. Survey fishing gear changed from Engel (white bars) to Campelen (black bars) in 1995.

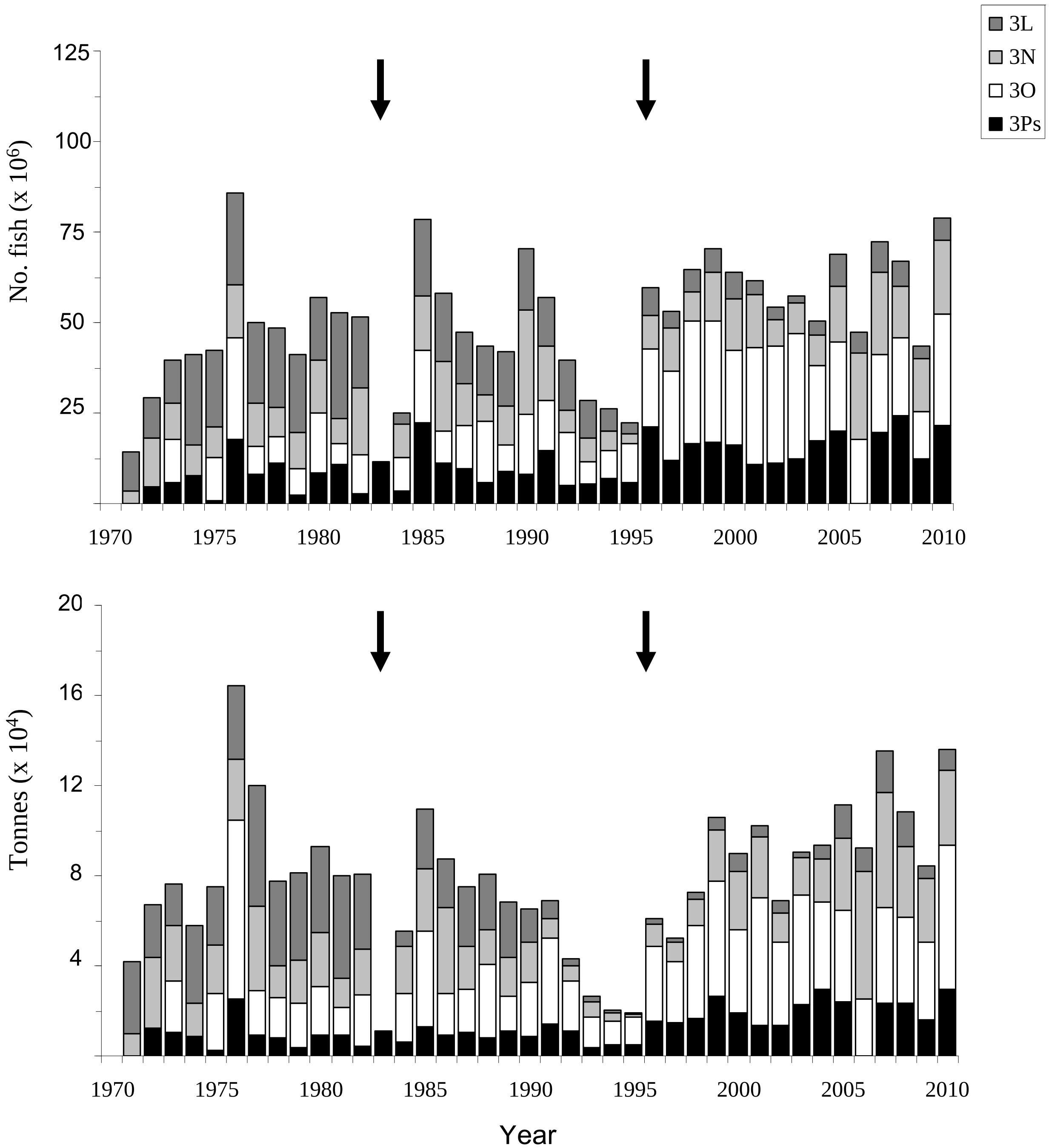

Figure 16. Spring survey abundance estimation for A. radiata in Div. 3LNOPs (1971-2010). Upper panel: number of fish, lower panel: biomass. Calculations are based on areal expansion projections of catch rates using the STRAP routine (see text for details). Black arrow denotes change in fishing gear: Yankee to Engel (1983), and Engel to Campelen (1996).

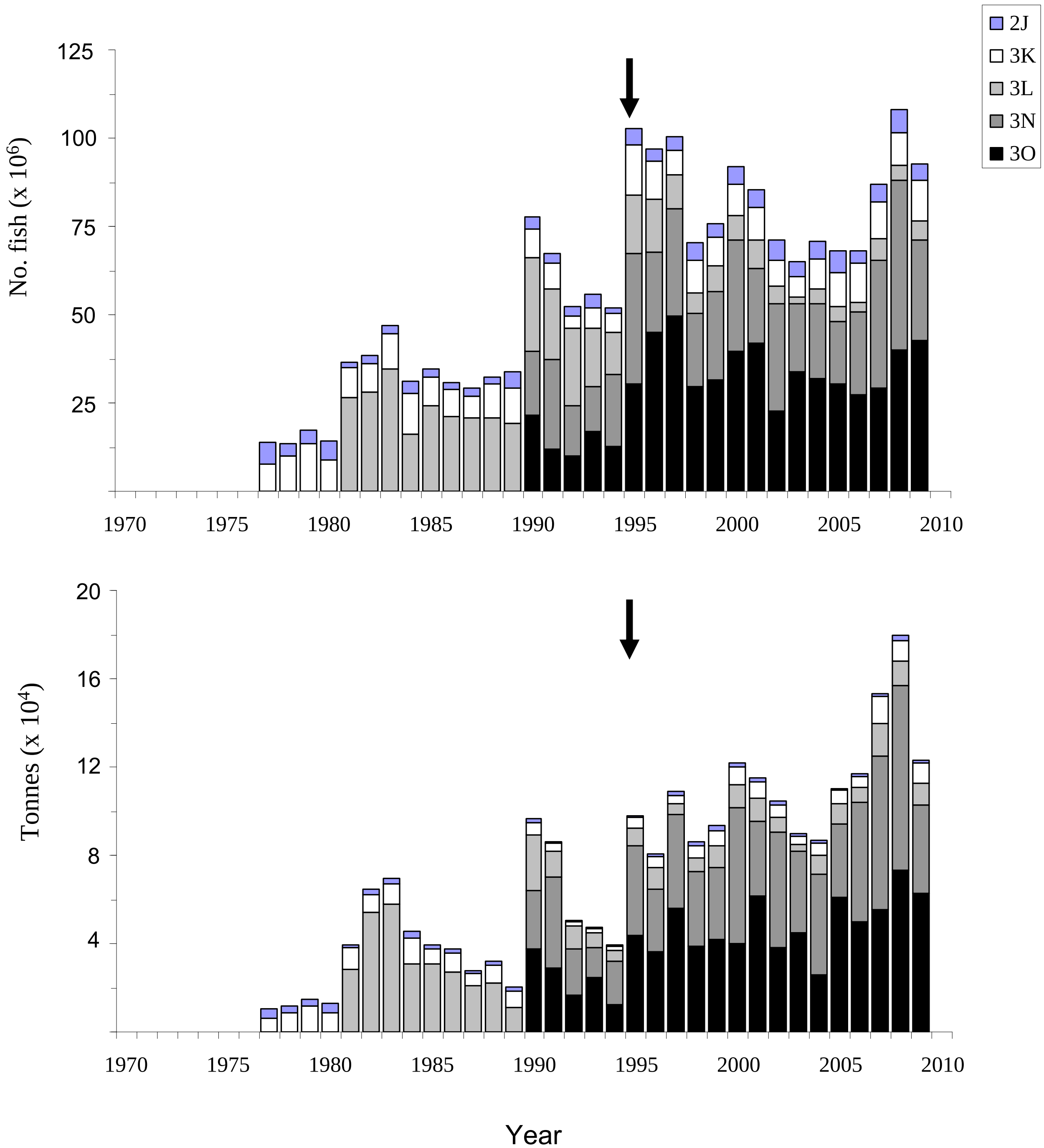

Figure 17. Fall survey abundance estimation for A. radiata in Divisions 2J3KLNO (1977-2010). Upper panel: number of fish, lower panel: biomass. Calculations are based on areal expansion projections of catch rates using the STRAP routine (see text for details). Black arrow denotes change in fishing gear: Engel to Campelen (1995).

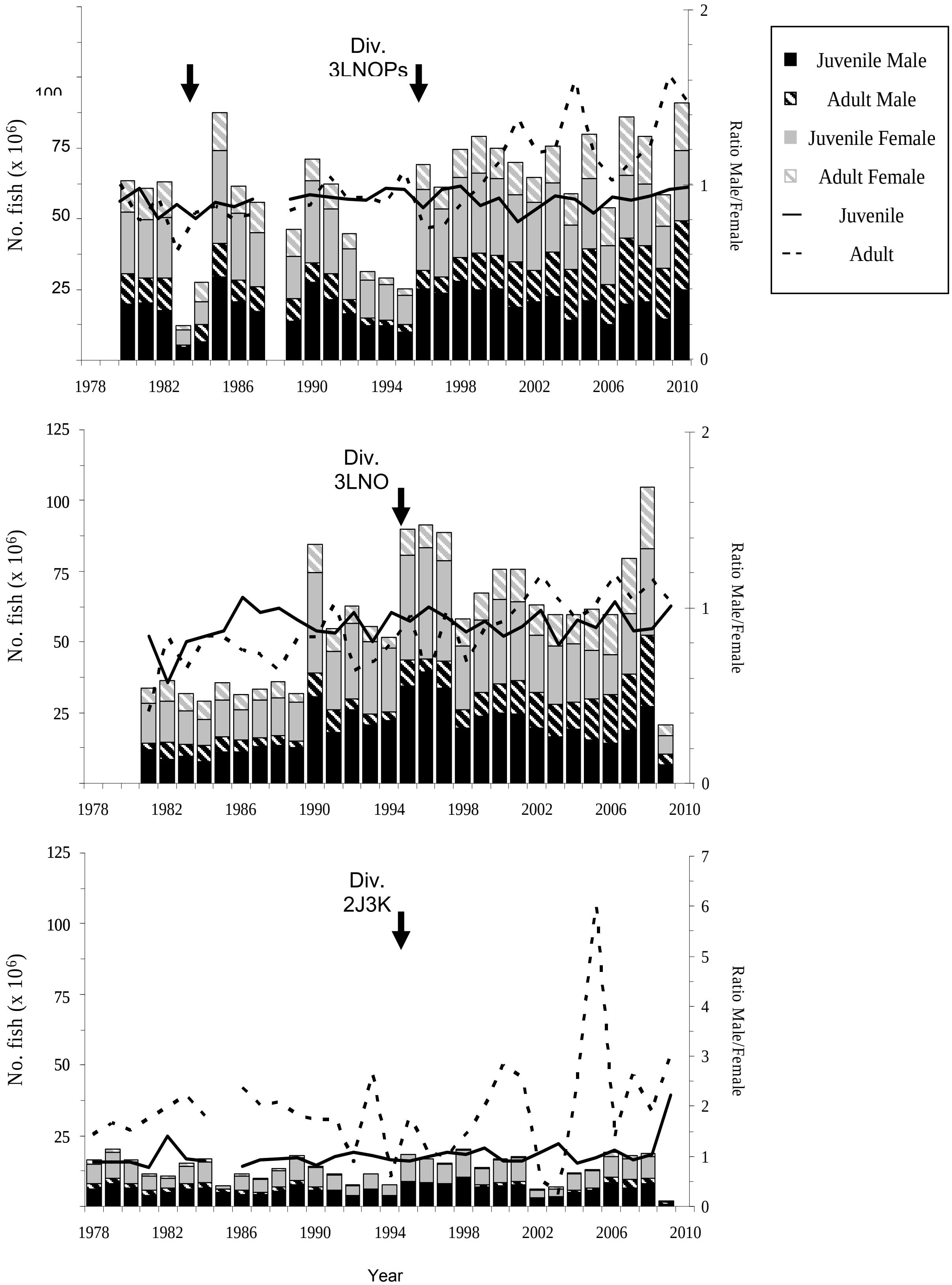

Figure 18. Survey abundance estimation and sex ratio for juvenile and adult males and females A. radiata for the combined Division 3LNOPs in spring (upper panel), and Division 3LNO and Division 2J3K in fall

(middle and lower panels). Black arrow denotes change in fishing gear: Yankee to Engel (1983), and Engel to Campelen (1995-96).

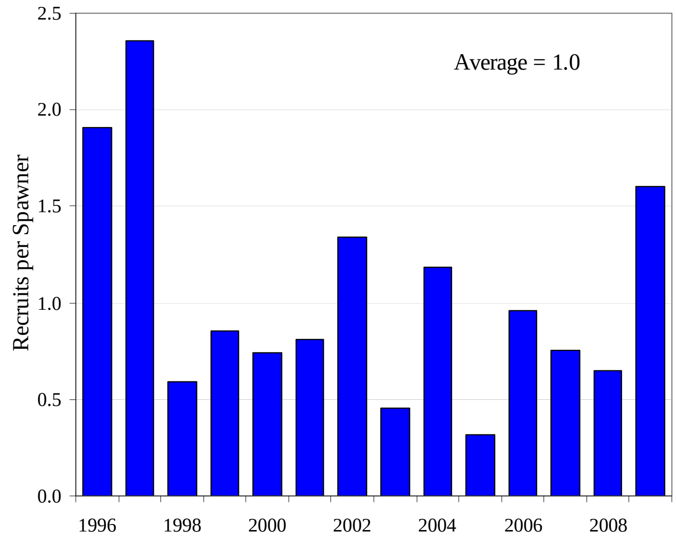

Figure 19. Recruit per spawner expressed as number of young-of-the-year (YOY) males and females A. radiata (#YOY/mature female in previous year) from Campelen spring surveys in Division 3LNOPs (1996-2009).

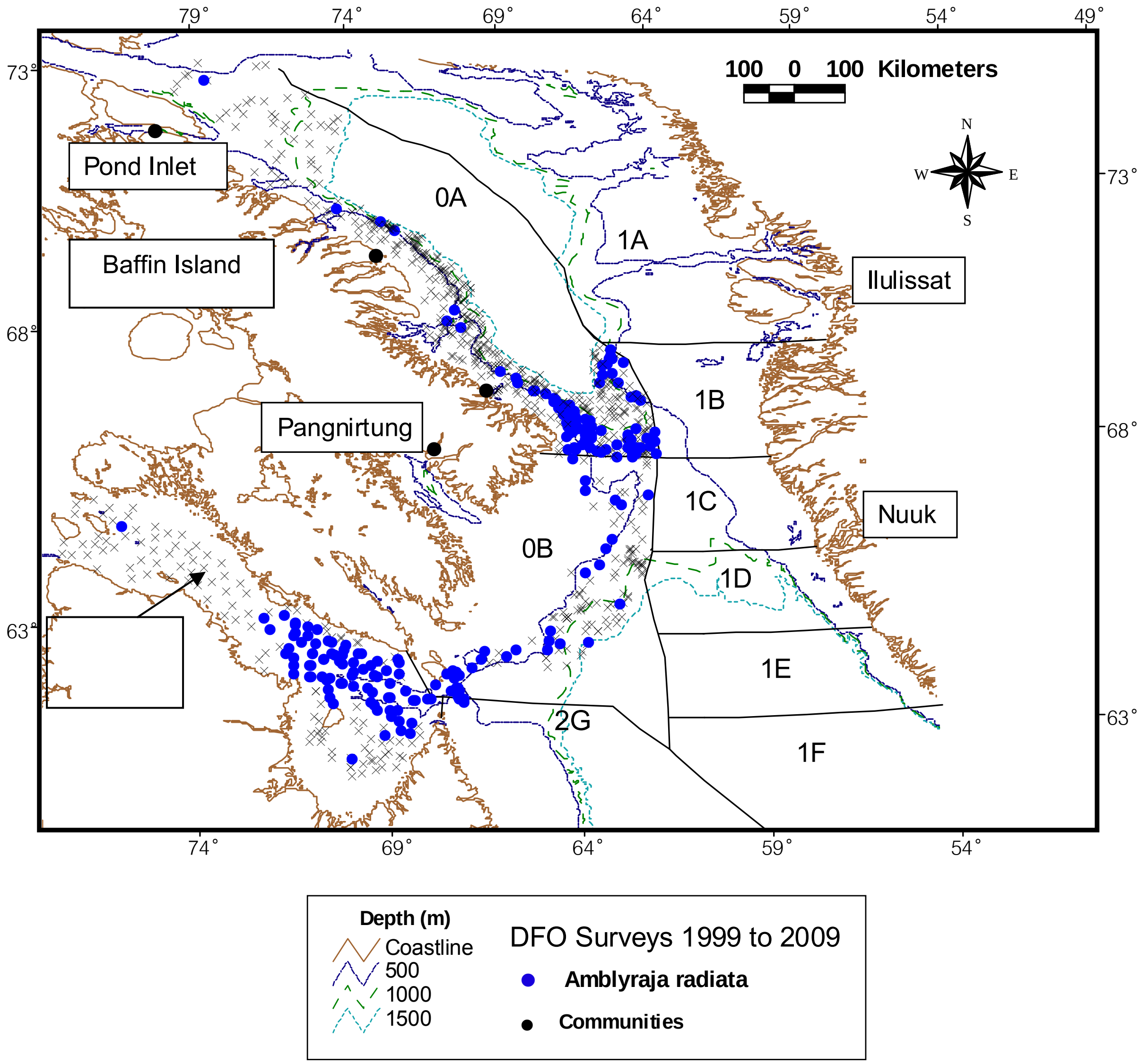

Figure 20. Distribution of DFO survey tows with the occurrence of A. radiata (blue circle) in NAFO SA0 and Hudson Strait/Ungava Bay (1999-2009). Depth information and tow locations with no catch (×) are also shown.

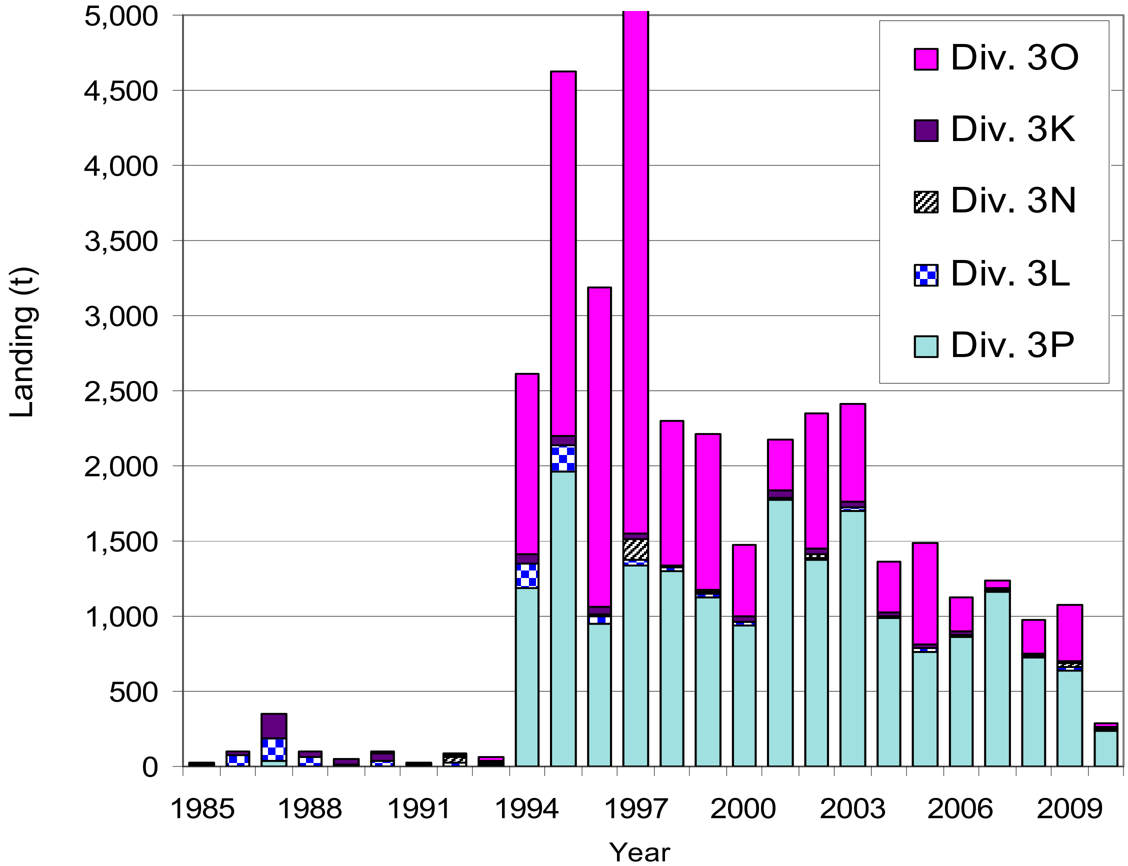

Figure 21. Canadian reported annual landings for A. radiata in Div. 3KLNOPs inside Canada's EEZ (1985-2010). The 2010 data are preliminary and include landings up to October of that year.

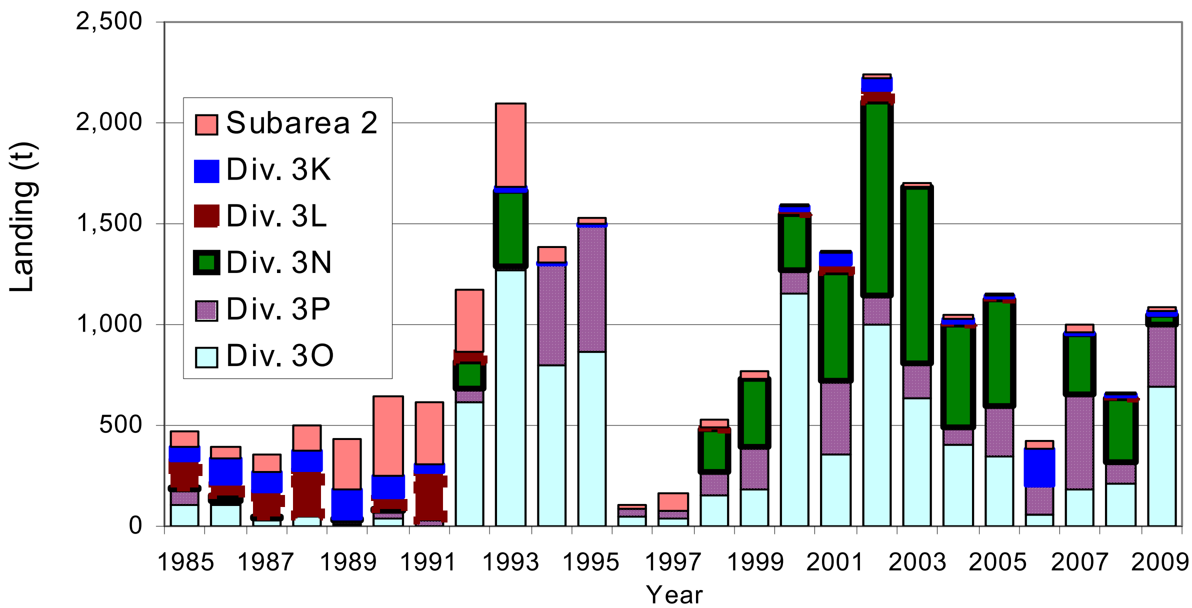

Figure 22. Observers' at-sea catch data for A. radiata prorated to total reported groundfish landings (ZIF) in Subarea 2 and Division 3KLNOP in Canada's EEZ (1985-2009).

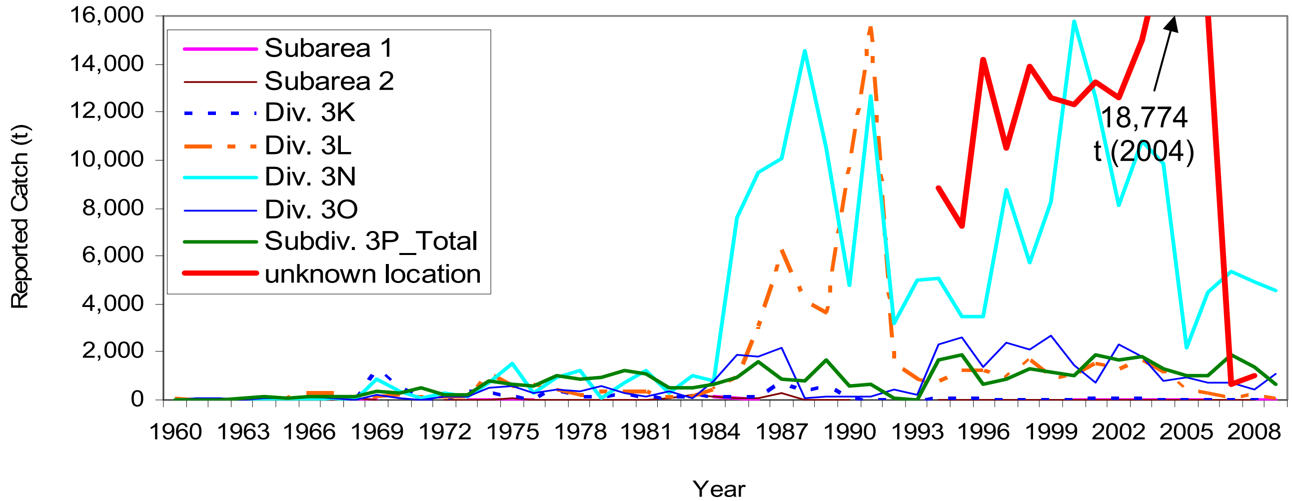

Figure 23. NAFO reported catches (1960-2009) for unspeciated skates in Division 3KLNOPs, Subareas 1 and 2 and unknown locations.

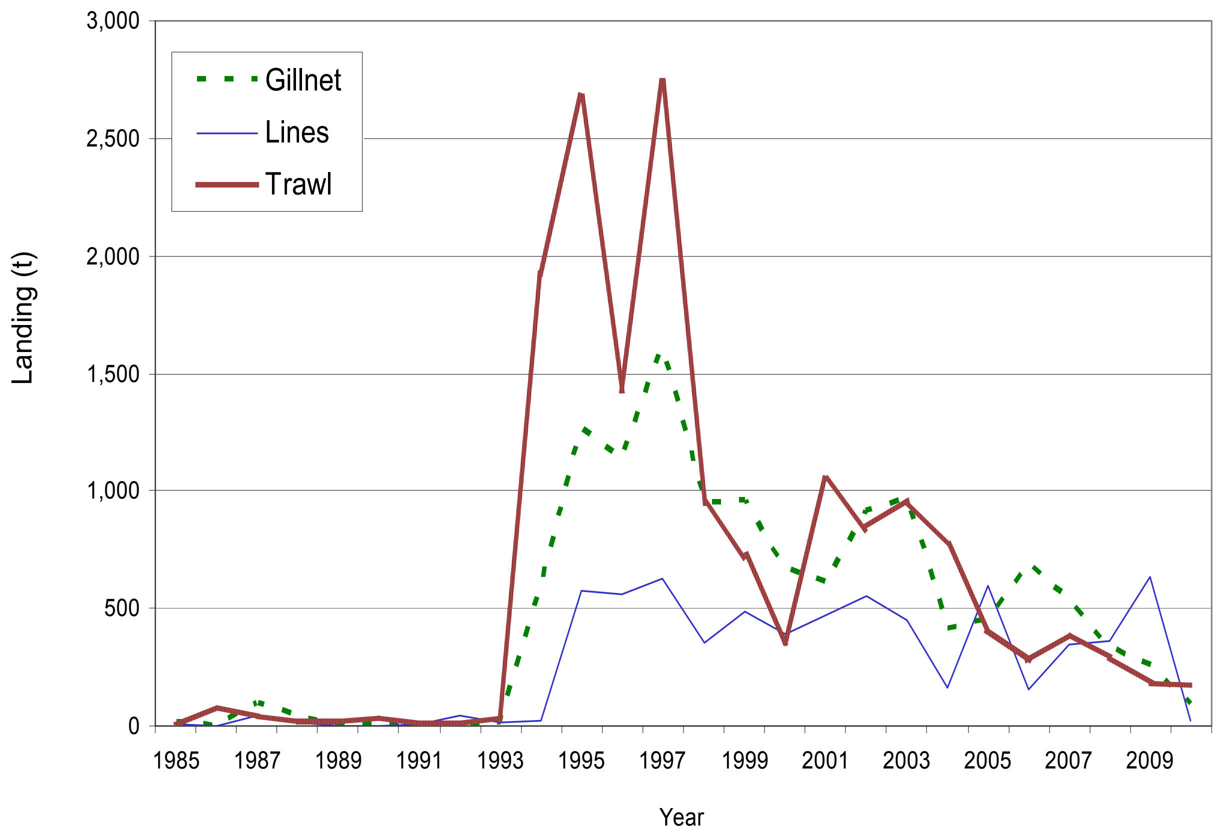

Figure 24. Canadian reported annual landings for A. radiata by fishing gear type in Canada's EEZ (1985-2010). The 2010 data are preliminary and include landings up to October of that year.

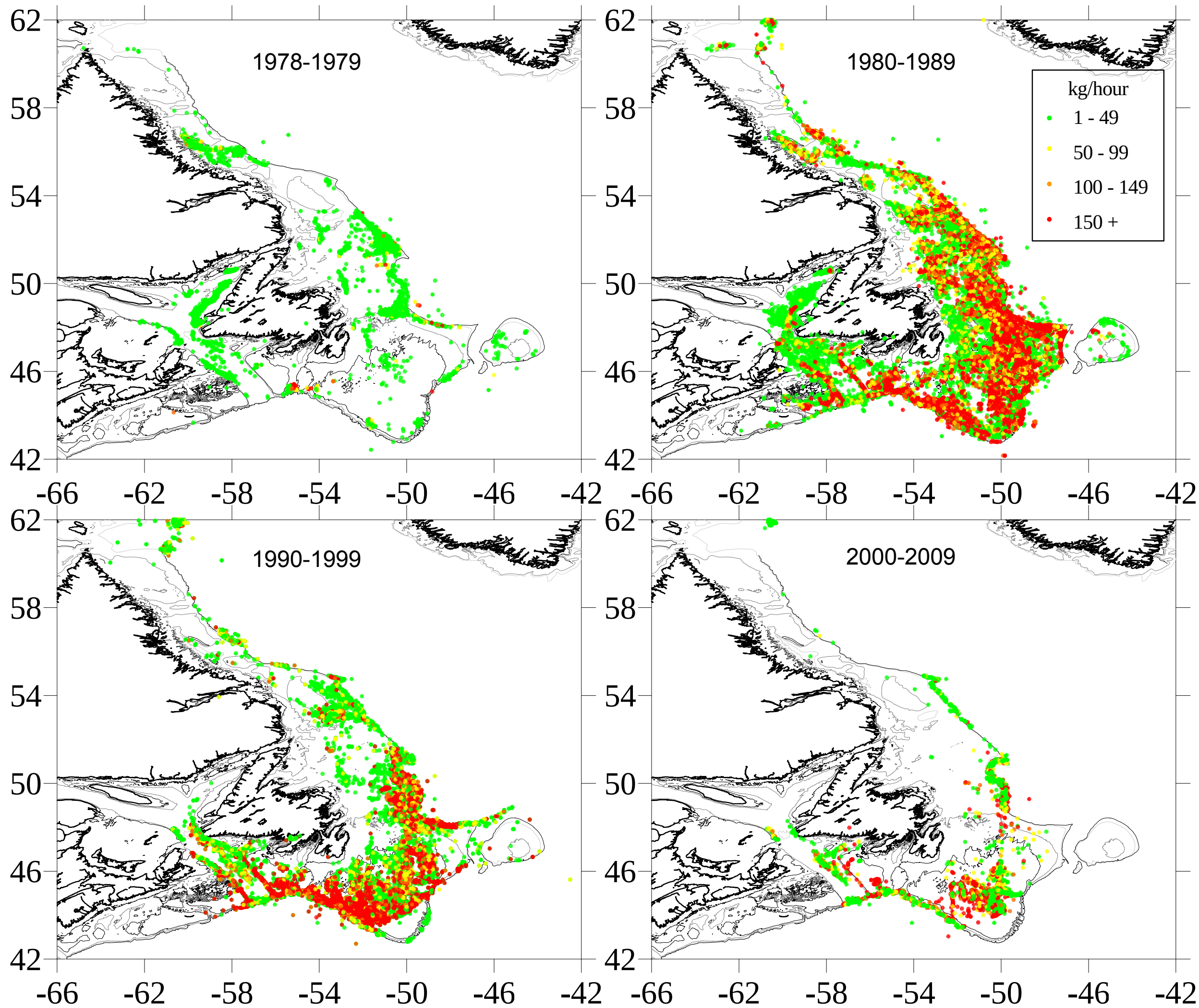

Figure 25. A. radiata catch rate (kg/hour) for bottom trawl fisheries directed at several demersal fish species (Atlantic cod, redfish, American plaice, witch flounder and yellowtail flounder) based on the Observers' at sea database (1978-2009).

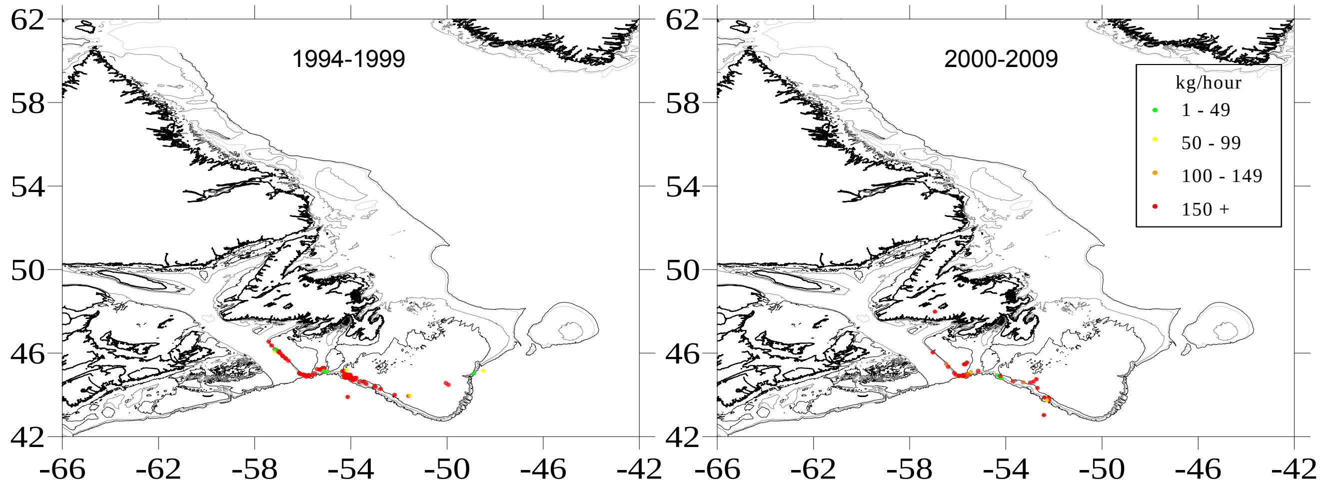

Figure 26. A. radiata catch rate (kg/hour) for bottom trawl fisheries directed at skates based on the Observers' at sea database 1994-2009).

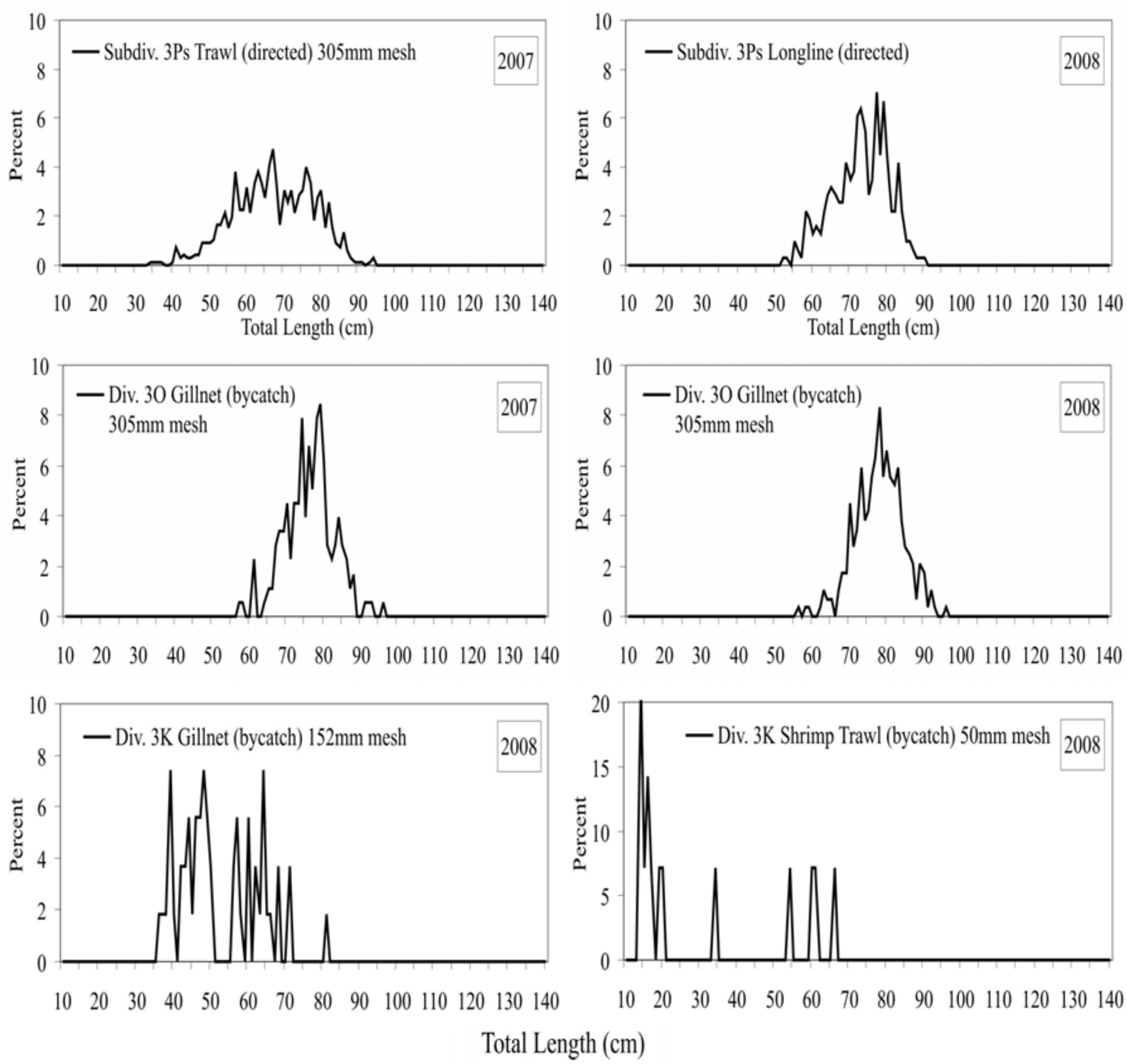

Figure 27. Observers' at-sea length frequencies of A. radiata in directed trawl and longline fisheries in Division 3Ps (upper panels), Monkfish directed gillnet fishery in Division 3O (centre panels), and shrimp gillnet and trawl fisheries in Division 3K (bottom panels).

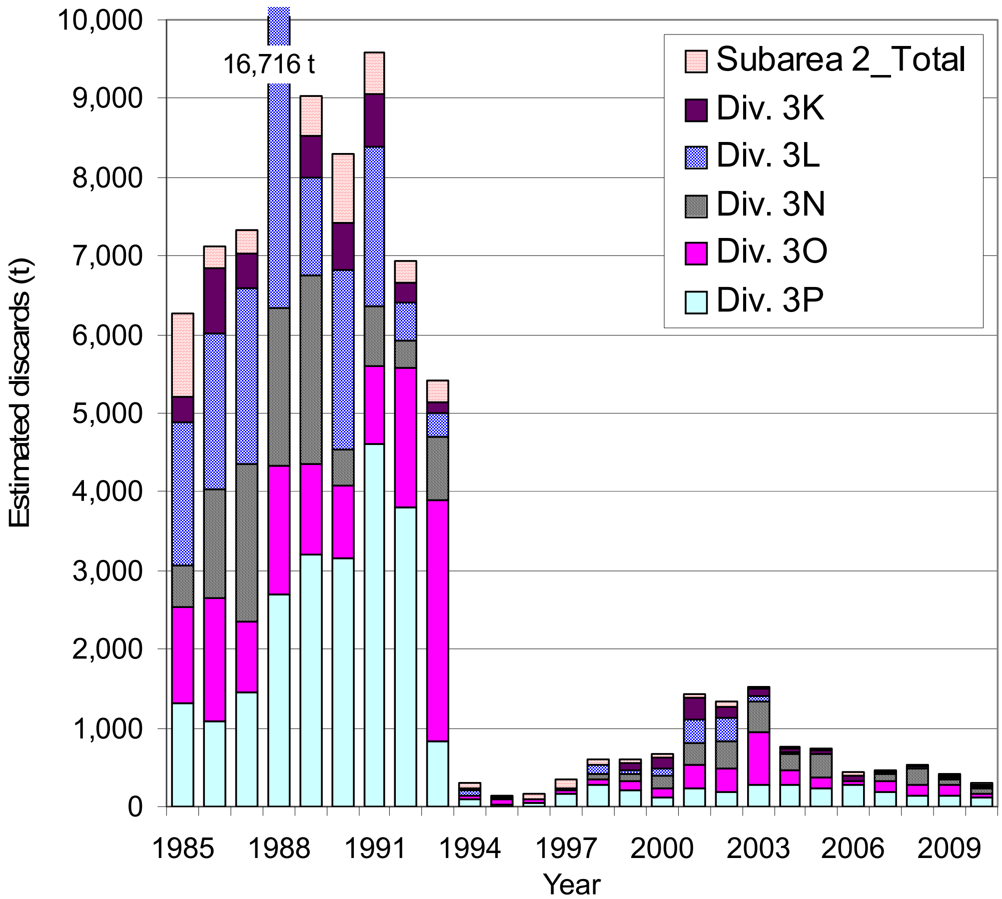

Figure 28. Estimated discards of A. radiata in Subarea 2 and Division 3KLNOPs according to the Observers' at sea skates discard data prorated to total reported groundfish landings (ZIF) between 1985-2010.

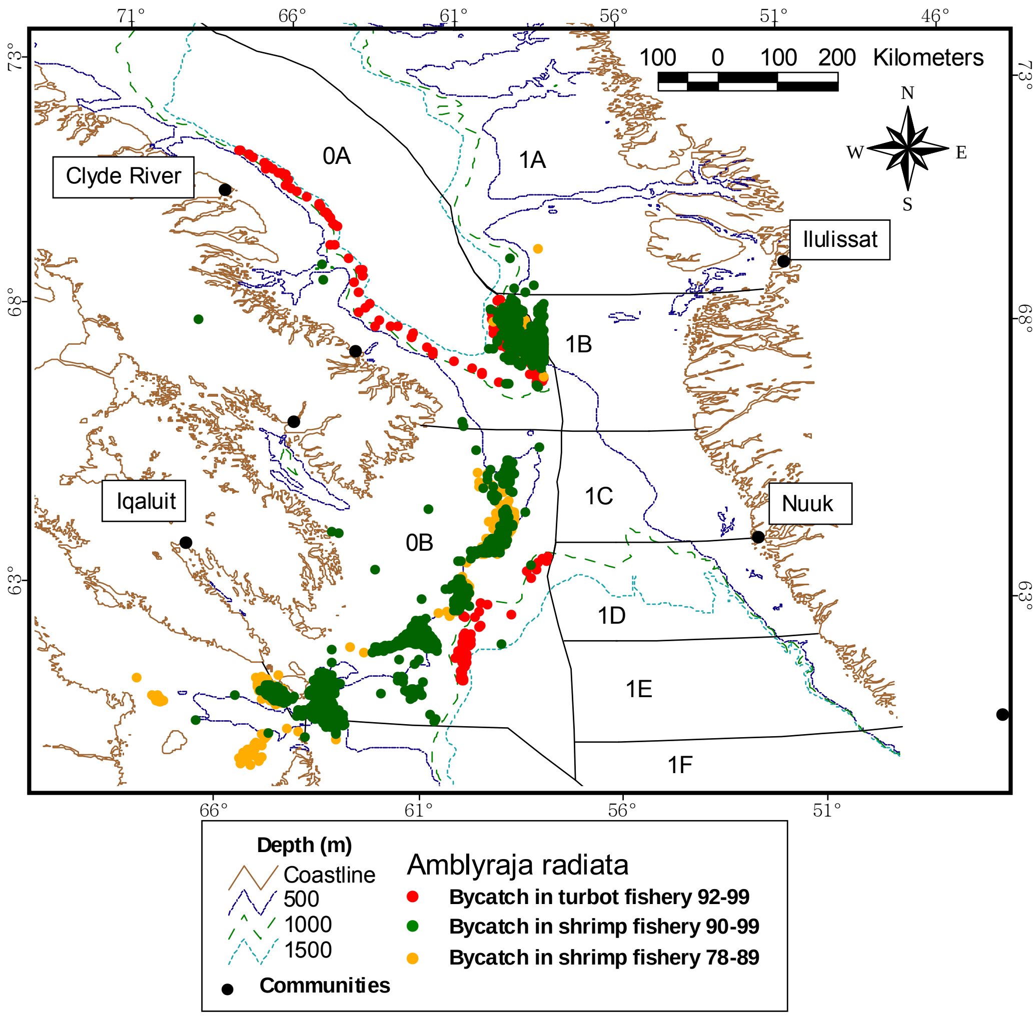

Figure 29. Distribution of tows with the occurrence of A. radiata bycatch in the Greenland halibut fishery in NAFO SA0AB since 1992 (red circle) and northern shrimp fishery in SFA 0, 1, 2, and 3 since 1979 (green and yellow circles). Depth information is also shown.

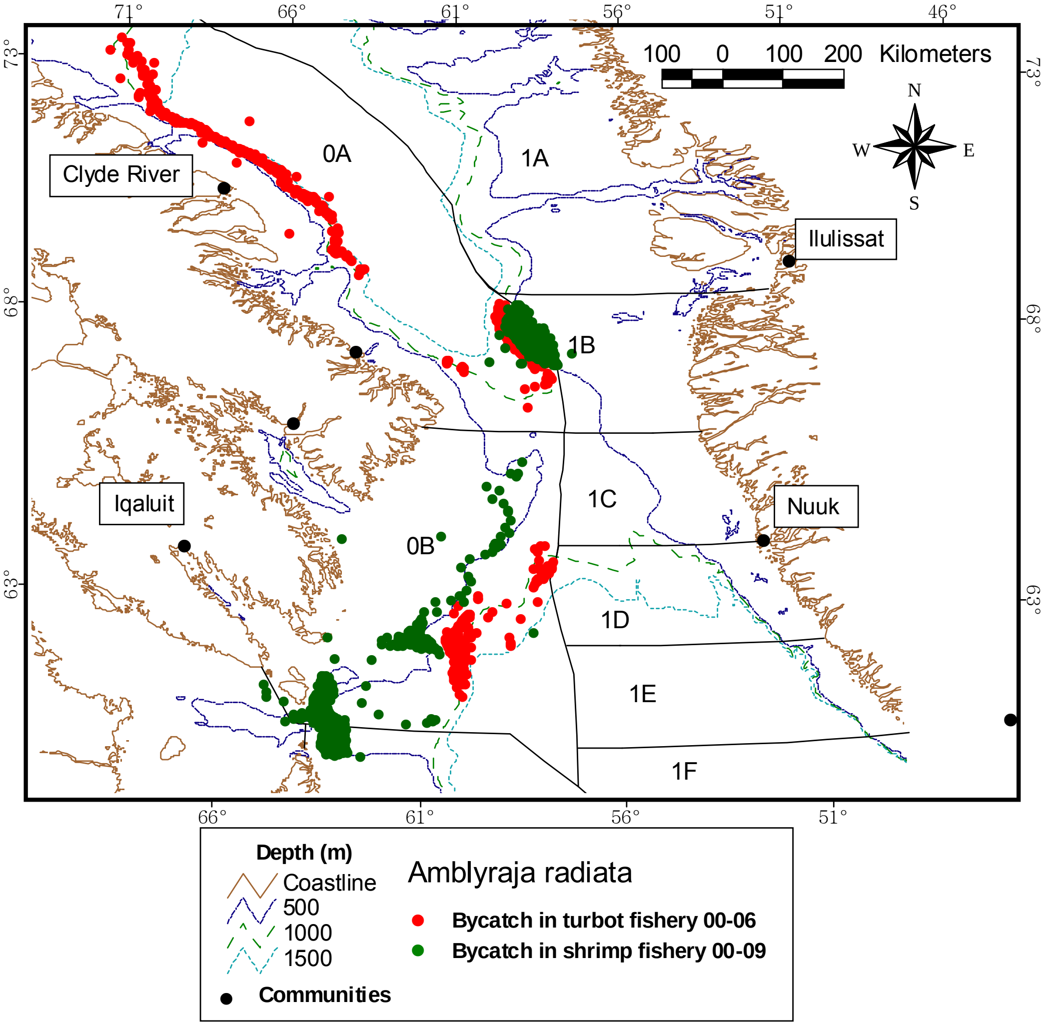

Figure 29 (cont'd.). Distribution of tows with the occurrence of A. radiata bycatch in the Greenland halibut fishery in NAFO SA0AB since 1992 (red circle) and northern shrimp fishery in SFA 0, 1, 2, and 3 since 1979 (green and yellow circles). Depth information is also shown.