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A review of the biology of Atlantic hagfish (*Myxine glutinosa*), its ecology, and its exploratory fishery in the southern Gulf of St. Lawrence (NAFO Div. 4T)

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Foreword

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ABSTRACT

Since 2011, four vessels have been licensed to conduct an exploratory fishery for Atlantic hagfish (*Myxine glutinosa*) in the NAFO Div. 4T9ab management area, located off northern Cape Breton, of the southern Gulf of St. Lawrence. Hagfish in this fishery are fished using baited barrels. This report reviews the biology of Atlantic hagfish, summarizes the current knowledge of its ecology in the southern Gulf, and how the fishery is managed in the southern Gulf and elsewhere. Atlantic hagfish is a primitive fish, known to occupy cold waters of full salinity. It is associated with soft sediments in which it burrows and it feeds on various invertebrates and small fishes, but also scavenges fish and marine mammal carcasses. In surveys of the southern Gulf, hagfish were captured on the slopes of the Laurentian Channel at depths > 260 m, at water temperatures mainly between 5 and 6°C, and salinities of 34 to 35 ppt. Prior to the 1990s, hagfish were only caught in small numbers and not every year in the southern Gulf survey. Survey indices indicate a considerable increase in hagfish abundance and occurrence in the southern Gulf during the 1990s, with annual fluctuations without a trend during the 2000s. A survey index for the 4T9ab management area, based on calibrated data from the northern and southern Gulf research vessel surveys, fluctuates widely without a clear trend, likely owing to the small number of survey tows conducted in this area annually. No data are available on the size at maturity of Atlantic hagfish in the Gulf of St. Lawrence. The minimum commercial weight of hagfish for buyers supplying the Korean market has been reported to be 80 g, or approximately 43 cm. Hagfish < 43 cm composed 21% to 72% of the number of hagfish caught in four commercial fishing trips sampled by observers and dockside monitors in 2012. Discarding occurs in the fishery and has exceeded 10% of the catch weight in two of the five years. Discarding may be partly due to spoiled catches when traps were deployed and untended for more than 24 hours. The potential of the hagfish resource to support exploitation is uncertain due to the lack of biological data, particularly their age structure, growth, and mortality, as well as the lack of capacity to assess population changes in response to fishing and the effects of unaccounted catch, particularly discarding.

Un aperçu de la biologie, de l’écologie, et de la pêche exploratoire à la myxine du nord (*Myxine glutinosa*) dans le sud du golfe du Saint-Laurent (Div. 4T de l’OPANO)

RÉSUMÉ

Depuis 2011, quatre navires ont été autorisés à mener une pêche exploratoire de la myxine du nord (*Myxine glutinosa*) dans la division 4T9ab de l’Organisation des pêches de l’Atlantique Nord-Ouest (OPANO), située au large de la côte Nord du Cap-Breton, dans le sud du golfe du Saint-Laurent. Dans le cadre de cette pêche, la myxine est pêchée au moyen de barils appâtés. Le présent rapport examine la biologie de la myxine du nord, résume les connaissances actuelles sur son écologie dans le sud du golfe et explique comment les pêches sont gérées dans le sud du golfe du Saint-Laurent et ailleurs. La myxine du nord est un poisson primitif qui occupe les eaux froides à salinité maximale. Elle est associée aux sédiments meubles dans lesquels elle s’enfouit, et elle se nourrit de divers invertébrés et petits poissons, mais aussi de carcasses de poissons et de mammifères marins. Dans le cadre de relevés menés dans le sud du golfe, des myxines ont été capturées sur le talus du chenal Laurentien, à des profondeurs supérieures à 260 m, à des températures de l’eau principalement entre 5 et 6 °C, et à une salinité entre 34 et 35 ppm. Avant les années 1990, les myxines n’étaient capturées qu’en petit nombre, et pas toutes les années de relevés du sud du golfe. Les indices du relevé montrent une augmentation considérable de l’abondance et de l’occurrence de la myxine dans le sud du golfe du Saint-Laurent au cours des années 1990, avec des fluctuations annuelles sans tendance au cours des années 2000. Un indice de relevé pour la zone de gestion 4T9ab, basé sur des données étalonnées de relevés menés par des navires de recherche entre le nord et le sud du golfe, varie largement sans montrer de tendance évidente, probablement en raison du petit nombre de traits de relevé effectués dans cette zone chaque année. Il n’y a pas de données disponibles sur la taille à la maturité de la myxine du nord dans le sud du golfe du Saint-Laurent. Le poids commercial minimal de la myxine pour les acheteurs qui approvisionnent le marché coréen est de 80 g, ou environ 43 cm. Les myxines de moins de 43 cm constituent de 21 % à 72 % du nombre de myxines prises lors de quatre expéditions de pêche commerciale échantillonnées par des observateurs en mer et des vérificateurs à quai en 2012. Des rejets ont lieu dans le cadre de la pêche et ont dépassé 10 % du poids des prises pour deux des cinq dernières années. Les rejets peuvent être en partie attribuables aux prises gaspillées lorsque des pièges sont déployés et non vérifiés pendant plus de 24 heures. Le potentiel des ressources en myxine à soutenir l’exploitation est incertain en raison du manque de données biologiques, notamment la structure selon l’âge, la croissance et la mortalité, ainsi que le manque de capacité à évaluer les changements dans la population en réponse à la pêche et les effets des prises non comptabilisées, notamment les rejets.

INTRODUCTION

Atlantic hagfish (*Myxine glutinosa*) commonly occurs on the continental shelves or their edges across the North Atlantic (Figure 1). Atlantic hagfish in the southern Gulf of St. Lawrence (sGSL) was, until recently, not commercially fished. Since 2011, applications have been made yearly to the DFO Gulf Region for exploratory permits to fish hagfish within the management area designated as 4T9a and b (Figure 2). This research document provides background information on Atlantic hagfish to assist in management strategies for developing a fishery in the sGSL. The report includes a general overview of the biology and ecology of Atlantic hagfish, its status in the sGSL, a description of fishing activities in the sGSL, and a review of similar fisheries on hagfish elsewhere in Canada, including approaches used to manage these fisheries. Lastly, this report assesses science requirements in support of the management of a developing Atlantic hagfish fishery in the sGSL.

BIOLOGY

The biology of hagfishes has received considerable interest and attention in aspects related to their evolution, morphology, physiology and genetics, owing mainly to their unique position in fish evolution. In spite of this important research base, much of hagfish life history and their population dynamics remains unknown.

Hagfishes and lampreys are frequently referred to as cyclostomes (Class Agnatha), or jawless fishes. These are the earliest forms of living vertebrates, distinct from gnathostomes, or the common jawed fishes. More recent classifications include hagfishes in the subphylum Craniata, but exclude hagfishes from the Vertebrata mainly because their notochord lacks rudimentary vertebral elements (Nelson 2006). The controversy concerning their classification relates to two views on their position in fish evolution: as a primitive vertebrate fish, most closely related to lampreys, or as a stage preceding the evolution of the vertebral column. Some evidence from DNA analyses points to a return to the original classification (Janvier 2010). Vertebral structures in the caudal region of the adult Japanese hagfish (*Eptatretus burger)* and in their embryos may indicate that hagfish have evolved with a vertebral column more similar to lampreys than previously thought (Ota et al. 2011).

Hagfishes, regardless of their classification, represent the earliest form of the living fishes, comprising one family (Myxinidae), 7 genera and about 70 species worldwide (Nelson 2006). They are thought to have originated in the Cambrian period, over 500 million years ago. A single specimen from Illinois (Bardack 1991) is a probable fossil hagfish dating from the Pennsylvanian age, some 300 million years ago. Due to their ancient origins and unique position in the evolution of fishes, there is hardly any aspect of their biology that is not unique or intriguing. Some popular accounts of their biology have been made by researchers such as Jensen (1966) and Martini (1998a) and a compendium of hagfish biology was edited by Jørgensen et al. (1998).

Atlantic hagfish are eel-shaped with a lateral compression posteriorly, otherwise round in cross section (Scott and Scott 1988; Martini and Flescher 2002). They have a single nostril at the tip of their snout and a mouth without lips surrounded by two pairs of barbels that serve a tactile function. Atlantic hagfish have no paired fins, fin rays or lateral line. They possess a single fin that is little more than a fold of skin beginning about two thirds back from the snout on the dorsal side, continuing around the tail, and ending on the ventral side about one third back from the snout. Two ventral gill pores are situated on opposite sides of the body a quarter back from the anterior end of the body, with the left opening noticeably larger than the right opening. Branchial openings are located at the origin of the ventral fin fold; a cloaca is found near the end of the tail from which digestive wastes, eggs and sperm are released. Their skin has no scales and is coloured brown, reddish, greyish red, or pink and mottled.

The size range reported for Atlantic hagfish varies between authors, partly due to geography and depth. Scott and Scott (1988) described their size as 46 to 61 cm, rarely longer. Martini et al. (1997a) reported hagfish caught by baited traps in the Gulf of Maine in 1994 that ranged from 17 to 95 cm (mean = 53 cm; n = 1,172). Gulf of Maine groundfish trawl surveys, aggregated from 1962 to 2002, caught hagfish between 20 and 70 cm, with occasional records of 91 cm hagfish (NEFSC 2003). Atlantic hagfish may reach smaller maximum sizes in more northern waters, although their size may be confounded by depth effects. In the sGSL, a survey with baited traps with 12.7 mm escape holes (SENPAQ 1992) recorded hagfish sizes between 15 and 56 cm, but with one large individual of 71 cm (mean = 34.4 cm, n = 10,244). With comparable gear and at similar depth, Grant (2006) recorded hagfish of 20 to 55 cm on the southwest slope of the Grand Bank (mean = 38.1 cm, n = 250). Off the SW Grand Bank, individual body size increased with greater depths over a depth range of 146 to 664 m (Grant 2006).

Atlantic hagfish are effectively blind, their eyes lack a vitreous body, have poorly differentiated retina and are covered by muscle (Locket and Jørgensen 1998). Despite their lack of sight, Atlantic hagfish are light sensitive and may be more active at night. Aside from their cryptic burrowing habits, they defend themselves from predators by a large output of slime. Two ventrolateral lines of mucous glands extend the entire length of the body. The mucus secreted by hagfishes expands on contact with seawater, filling the mouths of predators and potentially suffocating them. Their ability to coil their bodies while consuming prey and the predator evasion response through secretion of mucus was documented in a video posted online by the Museum of New Zealand Te Papa Tongarewa (accessed February 23, 2017).

When hungry, hagfish are capable of swimming rapidly using serpentine movements. They have acute smell and touch. They possess a tongue with two dental plates, each plate supporting two curved rows of keratinous cusps. The upper surface of their mouth has a short fang that is used to hold prey. These mouth parts make it possible for hagfish to grip and rasp the surface or flesh of large prey, thereby invading the carcasses of dead fish and marine mammals, usually through openings or soft tissues. Hagfish combine their rasping action with a unique ability to apply pressure against the prey by sliding a knot along the length of their body (illustrated in Strahan 1963 and Jensen 1966). In addition to their scavenging, Atlantic hagfish consume a range of fish and invertebrate (Martini 1998b).

Hagfish burrow into soft flocculent sediments where they remain coiled with their heads directed upwards. In a resting state, hagfish have exceptionally low blood pressure and metabolic rate. They are reported to survive up to seven months without food in aquaria (Jensen 1966) and possess biochemical adaptations and cutaneous respiration, permitting them to survive anoxic conditions, including being buried in sediments (Sidell and Beland 1980; Lesser et al. 1996; Malte and Lomholt 1998). Smith and Hessler (1974) estimated *in situ* respiration at 1,230 m for the hagfish *Eptatretus deani* at 0.10 µmol O_2 g^{-1} h^{-1}. These results point to an exceptionally low metabolic rate for hagfishes, consistent with a feeding strategy for fishes living in nutrient-poor conditions that maintain a quiescent state until food becomes available (Hessler and Jumars 1974).

Hagfishes are entirely marine and are at osmotic equilibrium with seawater (Hickman and Trump 1969). Due to their low capacity to osmoregulate, salinity is considered a limiting factor for all known hagfish species (Martini 1998b), with Atlantic hagfish preferring salinities at 32-34 ppt. Atlantic hagfish can be maintained in captivity at 0-4°C and tolerate temperatures up to 15°C (Martini 1998b). In the Gulf of Maine, Martini (1998b) found Atlantic hagfish at depths of 30 to 200 m where temperatures were below 4°C and salinities were above 32 ppt. In a trawl survey that covers the area between the Gulf of Maine and Cape Hatteras, Atlantic hagfish are found across a broad range of depths and temperatures, but are most commonly captured between 150 and 250 m and at 5-10°C (NEFSC 2003).

Uncertainty persists as to the details of hagfish reproduction, mainly due to their inaccessibility and the impossibility of observing their reproductive cycle in captivity. All hagfish species produce small amounts of eggs and sperm. They lack a copulatory organ and the mode of fertilization remains unclear. Mature eggs are ovulated to the abdominal cavity, pass through the cloaca and are assumed to be fertilized externally (Walvig 1963; Patzner 1998). Hagfish gonads are located in a mesenterial fold on the right side of the abdominal cavity. The female ovary forms in the upper two thirds of the fold; the male testis forms in the posterior one third. The gonads of both sexes may appear in the same individual, but rarely with both sexes developed, resulting in hagfishes often referred to as non-functional hermaphrodites. Female Atlantic hagfish produce a small number of large ovoid shaped eggs (usually 20 to 30 eggs, 25 mm in length; Martini and Flescher 2002). Martini et al. (1997a) reported that of 122 sampled Atlantic hagfish in the Gulf of Maine that were examined histologically for sex and reproductive state, all fish up to 40 cm in length were sexually immature. A quarter of Atlantic hagfish measuring > 40 cm were sexually sterile, i.e. without macroscopically identifiable gonad tissue. The sex ratio in their sampling was about 10:1 in favour of females. Their sampling, conducted from June to August, produced a range of egg stages at any given time, suggesting that there is no specific breeding season for Atlantic hagfish. Martini and Beulig (2013) have found a similar lack of seasonality in the annual reproductive cycle of a New Zealand stock of the hagfish *Eptatretus cirrhatus*, using a similar classification of female development stages based on length classes of developing ova. Powell et al. (2005) suggested seasonality in Atlantic hagfish maturity based on changes in gonadal hormone levels, with spawning possibly in April to May, but this is not yet confirmed for other populations.

Their lack of calcified body structures renders it impossible to determine the age of hagfish. Despite some success at identifying growth bands in the statoliths of sea lampreys (Beamish and Northcote 1989), the same structures have not proved useful for aging the hagfish *Paramyxine nelsoni* (Lee et al. 2007). Foss (1963) reported two tag recoveries of Atlantic hagfish in Norwegian waters that suggest slow growth. Tagged at lengths of 27.0 and 36.1 cm, the fish gained 0.5 and 2.1 cm after 29 and 11 months respectively. Based on their low metabolic rate, sedentary behaviour and their occurrence in areas of deep cold waters, it appears likely that they are slow growing, long-lived fishes. Other aspects of their biology indicate that they have low reproductive potential, notably due to their low fecundity, their size at maturity and their apparent lack of annual spawning. These factors alone have led some authors to question whether Atlantic hagfish can sustain exploitation in the long term (Martini et al. 1997a, 1997b).

DISTRIBUTION AND ECOLOGY

Atlantic hagfish are present on both sides of the temperate North Atlantic (Figure 1). On the western side, they are found from Davis Strait and Greenland, off Labrador and Newfoundland, in the Gulf of St. Lawrence and the Gulf of Maine, and along the continental slope to the coast of Florida (Martini and Flesher 2002). They are also reported from the South Atlantic off the southern coasts of Argentina and Chile, the Straits of Magellan and off South Africa (Martini and Flesher 2002). Throughout their distribution, Atlantic hagfish occur at depths of more than 30 m (Scott and Scott 1988).

Broad-scale genetic analyses are lacking to determine the population structure of Atlantic hagfish at any scale. Eastern and western Atlantic hagfish cannot be distinguished by morphometric characteristics. However, hagfish distribution is not continuous throughout the North West (NW) Atlantic and there are regional differences in the maximum size and size at sexual maturity (DFO 2009a).

Hagfish may be overlooked or underestimated in trawl surveys due to low catchability to the gear (NEFSC 2003; Martini 1998b). Baited traps are more effective at capturing hagfish and have been used to estimate their density and biomass, although some assumptions required to derive estimates are difficult to verify. Wakefield (1990) estimated the biomass of *E. deani* at 600 m visually at 11,800 kg km^{-2} in an area off central California where trawling estimated hagfish biomass at 700 kg km^{-2}. Assuming a homogeneous distribution and a similar response to the bait stimulus, Martini et al. (1997b) estimated Atlantic hagfish biomass at 8,119 kg km^{-2} at 120 to 150 m depth in the Gulf of Maine. The authors derived their estimate using an ambient measured current velocity of 15 cm s^{-1} and an estimated swimming speed of 1 m s^{-1} for hagfish, based on data in Foss (1968). The estimate reported in Foss (1968) is based on a single field observation of a 30 cm long Atlantic hagfish pursued by an underwater diver. The hagfish moved over 10 m roughly at the maximum speed of a diver, judged to be about 1 m s^{-1}. Flume studies on *Eptatretus cirrhatus* indicate that 20 cm s^{-1} is the approximate aerobic swimming capacity for this species (Davison et al. 1990) suggesting that the estimate by Foss (1968) may be high in the context that it was used for the foraging area of hagfish.

Given local biomass estimates of several tonnes per km^2, Martini (1998b) has questioned whether hagfish can maintain their populations on scavenging alone. His literature review on hagfish feeding indicates a wide range of food items, with invertebrate organisms as their primary diet (Martini 1998b). Shelton (1978) found that Atlantic hagfish collected in the North Sea consumed mainly the shrimp *Pandalus borealis.* Martini et al. (1997b) found similarities between benthic communities described by Shelton (1978) and those in the Gulf of Maine where *P. borealis* is an important commercial shrimp (as elsewhere in the NW Atlantic, including the Gulf of St. Lawrence). In the Gulf of Maine, the estimated population of Atlantic hagfish would require the caloric equivalent of 18.25 tonnes of shrimp, 11.7 tonnes of sea worms and 9.9 tonnes of fish annually (Martini 1998a). He concluded that, by their population size and combined energy requirements, Atlantic hagfish are an important component of the substrate ecosystem of the Gulf of Maine (Martini 1998a).

Hagfishes are morphologically adapted for burrowing (Martini 1998b), a behaviour that is important to their ecology and to their role in the ecosystem. Atlantic hagfish may burrow frequently to seek cover or to pursue prey items. The burrows of Atlantic hagfish are transitory, collapsing once the fish emerges. Located invariably in soft muddy sediments, the burrowing action of hagfishes, particularly in anoxic areas, is considered to have an ecological engineering role in the re-suspension of marine sediments. Hagfish may play an important role in processing dead fish and marine mammals, including the discards of some commercial fisheries (Martini 1998b). Shelton (1978) examined the diet of Atlantic hagfish in the North Sea and concluded that they were active benthic predators filling an ecological niche comparable to large, burrowing errant polychaetes. Where hagfish are abundant, they may also play an important role in marine ecosystems through substrate turnover and nutrient recycling (Martini et al. 1997b; Martini 1998b).

Atlantic hagfish are reported to be consumed by Atlantic cod (*Gadus morhua*), white hake (*Urophycis tenuis*) and spiny dogfish (*Squalus acanthias*). Hagfish eggs have been reported from the stomachs of cod and Atlantic halibut (*Hippoglossus hippoglossus*) (Scott and Scott 1988; Martini and Flescher 2002). Harbor seal (*Phoca vitulina*) and harbor porpoise (*Phocoena*

phocoena) have been identified as marine mammal predators of Atlantic hagfish (Martini and Flescher 2002; Smith and Gaskin 1974).

RESEARCH DATA IN THE GULF OF ST.LAWRENCE

Data on Atlantic hagfish in the Gulf of St. Lawrence are available from two main sources: trawl surveys that have been conducted yearly in the southern and northern sectors of the Gulf and a baited trap survey targeting hagfish that was performed in the western part of the Gulf. Each data source has advantages and limitations. The trawl surveys provide time series of hagfish abundance trends spanning several decades. However, hagfish tend to be poorly represented in trawls and trawl-based estimates of population density and abundance are likely to be underestimated (NEFSC 2003). Surveys using baited traps that target hagfish are effective but potentially costly to perform. In the Gulf, only one such survey was conducted in 1992 (SENPAQ 1992).

SOUTHERN GULF ANNUAL TRAWL SURVEY

The annual research vessel (RV) trawl survey divides the southern Gulf into 24 strata, based mainly on depth (Figure 2). Three additional inshore strata were added in 1985, but these are excluded from the analyses presented here, as no hagfish have ever been caught near shore. The number of trawl sets allocated to each stratum varies as a function of the stratum size, with fishing locations chosen randomly within each stratum. Abundance is expressed as the stratified mean catch, calculated as the weighted mean of catches averaged in each stratum. Sampling methods for the RV survey were outlined in Hurlbut and Clay (1990). Some of these methods include standardized trawl gear, deployed on the bottom for 30 minutes at a tow speed of 3.5 knots. The depth, temperature and salinity, along with other hydrographic data, are recorded at each sampling location.

Some changes are inevitable in RV surveys due to aging research vessels or program requirements. The survey trawl gear was changed once, in 1985, and vessel changes were made in 1985, 1992 and 2005. The survey was conducted during daytime until 1985, when a larger research vessel was acquired, making it possible to sample over 24 hours. These gear and vessel changes were made following comparative fishing experiments to determine whether the changes incurred a significant effect on species catches or their size distribution. No significant effect due to vessel or gear changes was found for Atlantic hagfish (Benoît and Swain 2003a; Benoît 2006). However, a significant diel effect was detected with more hagfish caught at night than during daytime for the vessel that was used from 1992 to 2005 (Benoît and Swain 2003b). The survey data have thus been standardized to daytime equivalent catches for that period.

The number of trawl tows in the RV survey increased with 24-h sampling and as the duration of the survey increased (Figure 2). Before 1984, fewer than 75 tows were made in each survey, whereas after 1990 the number of tows in the survey frequently surpassed 170. Atlantic hagfish were consistently limited to the deep strata (415, 425, 437 and 439; Figure 2) where 97% of their catches were made. In most years until 1983, there were 10 tows conducted yearly in those four “hagfish strata”. This increased and, since 1996, the number of tows in the key strata for hagfish has been 20 or more in 10 survey years. Note that in 2003, the research vessel was incapacitated due to a fire. The disabled vessel was replaced with an uncalibrated trawler, but delays resulted in reduced survey coverage particularly in “hagfish strata”. As a result, the 2003 survey was excluded from further analysis.

Standardized Atlantic hagfish abundance indices based on the RV survey fluctuated at a low level for most of the first three decades of the RV survey, but increased in the mid-1990s

(Figure 3a). The mean catch fluctuates widely and its confidence intervals are wide, even in the period since 1998 when hagfish abundance appears to be relatively high. This makes it difficult to discern any trend in the short term, although in the long term it appears that hagfish abundance since the late 1990s has been greater than during the period from 1971 to the early 1990s.

The stratified percent occurrence of hagfish in the RV survey followed a similar trend to the abundance index, increasing through the 1990s, followed by a sustained high level since 2000. Since 1997, Atlantic hagfish have occurred in 6-10% of survey tows in all years except one (no data for 2003), whereas in the previous 26 survey years their occurrence ranged between 0 and 5% in all but two years (Figure 3b).

The relationship of hagfish catches relative to the sampled depth, temperature and salinity was examined using cumulative density functions (Perry and Smith, 1994) to identify habitat associations. These functions were computed for the 2006 and 2007 sGSL RV surveys when hagfish were abundant. The survey covered depths ranging between 25 and 361 m in 2006, 22-353 m in 2007; temperatures 0.2-17.1°C in 2006, 0-17.4°C in 2007; salinities 28.2-34.8 ppt in 2006, 29.1-34.9 ppt in 2007.

Habitat selection was similar in both years (Figure 4). As might be inferred from the distribution maps, hagfish selected the deepest sampled areas in the sGSL with approximately 90% of hagfish caught at depths greater than 260 m in 2006 (83% in 2007), a depth zone that represented about 6% of the area covered by the survey in both years. Bourdages and Ouellet (2011) conducted a similar analysis of depth selection in nGSL RV surveys from 1990 to 2009. They reported hagfish occupying depths greater than 200 m, as in the sGSL, with 5th and 95th percentiles of cumulative catches at 224 and 452 m, respectively. Hagfish, in the sGSL, occupied a narrow temperature range of 5 to 6°C in both years (Figure 4). Hagfish also selected salinities between 34 and 35 ppt in both years, the uppermost 10% of salinities encountered in the two surveys.

The length composition of hagfish catches in the RV survey tends to be sparse and highly variable (Benoît et al. 2003). Low abundance makes it difficult to discern any pattern in hagfish size composition over the first 25 survey years, even when stratified mean catches are averaged in 5-year periods (Figure 5). Since 1996, a period of relatively high hagfish abundance in the sGSL RV survey, the size composition has remained concentrated within the 30 to 45 cm length range with modal sizes appearing between 30 and 35 cm and mean and median lengths varying between 35 and 36 cm.

Annual length frequencies in the sGSL RV survey appear highly variable, even in the recent period of relative high abundance. The number of measured hagfish in the 10 most recent surveys ranged from 13 to 114 fish annually, contributing to the variability in size composition (Figure 6). The data do not display recurrent length modes from which inferences can be made concerning growth and recruitment of Atlantic hagfish.

The length-weight relationships for Atlantic hagfish in the Gulf of St. Lawrence originate from two sources: data gathered in the RV surveys and an intensive sampling conducted in 1992 (SENPAQ 1992). The RV data were aggregated over the years since 1993 when electronic balances were used aboard the research vessels. Before that period, as in the SENPAQ study, fish were weighed with mechanical spring balances in the sGSL. Grant (2006) reported that Grand Bank hagfish appeared to be shorter and heavier at a given length than hagfish in the Gulf of Maine. It appears that hagfish in the sGSL and in NAFO 3PN (SW Newfoundland) are intermediate in weight-at-length to Grand Bank and the nGSL in the upper range and Gulf of Maine populations in the lower range of the length-weight relationship (Table 1; Figure 7).

NORTHERN GULF ANNUAL TRAWL SURVEY

The northern Gulf RV survey provides a wider coverage of the estuary and deep channels of the Gulf than the trap survey, areas preferred by Atlantic hagfish in the Gulf of St. Lawrence (Figure 8). The survey has been conducted in August every year since 1984. The survey area is divided into 52 strata and covers a depth range from 37 m to over 500 m (Bourdages and Ouellet 2011).

Recorded catches of hagfish in the northern Gulf RV survey started in 1990 and length measurements on hagfish began in 2003 (Archambault et al. 2014). Since 1990, the RV surveys of the northern and southern Gulf have been made with different trawls and fishing procedures. The northern Gulf survey changed its research vessel and trawl in 2004 and 2005, developing conversion factors for species catches over two years of comparative fishing (Bourdages et al. 2007). From 1990 to 2005 the survey was performed using the trawler *CCCG Alfred Needler* using the URI trawl; since 2004, it was conducted aboard the *CCCG Teleost* using the Campelen trawl (boats and trawls are also described in Bourdages et al. 2007). Bourdages et al. (2007) reported a significant difference between the catch rates of the two vessel-gear combinations, a significant effect of hagfish body length, but no significant day-night effect.

The abundance and biomass of Atlantic hagfish in the northern Gulf RV survey have varied over time without any clear trend (Figure 9). The mean number per tow has ranged between 8 and 51 hagfish in the northern Gulf, whereas it has never reached one hagfish per tow in the southern Gulf. Aside from the use of a different trawl in the two surveys and differences in the area swept by standard tows, the difference in catch rates also reflects the limited distribution of hagfish (and higher proportion of null catches) in the southern Gulf. Bourdages and Ouellet (2011) have shown that hagfish occur in roughly a third to over half of the stations sampled in the nGSL survey from 1990 to 2009.

INTERCALIBRATION OF THE NORTHERN AND SOUTHERN GULF SURVEYS

Analyses were undertaken to estimate the relative catchability of hagfish to the southern Gulf September trawl survey and the northern Gulf August trawl survey to allow the combination of the two surveys in a standardized time series. These two surveys cover an overlapping area that is found in three strata of the September survey (415, 425 and 439). Data for both surveys were selected based on the area of overlap and the years 1990 to 2015. Sets from the August survey were attributed to the September survey strata based on their respective geographic positions using the ‘point.in.polygon’ function in the ‘sp’ package for R (Bivand et al. 2008). For the analyses, a stratum-year factor was created, with levels for each stratum and year combination. Only those stratum-year combinations with sets from both surveys were retained. The relative catchability of the surveys was estimated using a negative binomial generalized linear mixed-effects model of the form:

$$Y_{i,s} \sim NB(\mu_{i,s}, k)$$

$E(Y_{i,s}) = \mu_{i,s}$ and $\mathrm{var}(Y_{i,s}) = \mu_{i,s} + \frac{\mu_{i,s}^2}{k}$

$\mu_{i,s} = \exp(\beta_0 + \beta_1 X + \delta_s + Z_{i,s})$ and with $\delta_s \sim N(0, \sigma^2)$

where $Y_{i,s}$ is the catch of hagfish in set *i* in stratum-year *s*, *X* is a factor for survey (a fixed effect), *k* is the estimated negative binomial dispersion parameter, δ_s is a random effect for stratum-year and $Z_{i,s}$ is an offset term to account for swept areas and differences in relative catchability within surveys related to vessel, gear and diel effects. The parameter β_1 is the relative catchability of the two surveys. The August survey was taken as the baseline such that August survey catches can be transformed to September survey equivalents by multiplying them by $\exp(\beta_1)$.

The analysis above was conducted separately for catch in numbers and catch in mass (kg). A significant difference in the estimates of β_1 between the two analyses would indicate size-dependence in the relative catchability. Strictly speaking, the negative binomial model, which is meant for count data (integers), is not appropriate for the mass data. While the variance estimates from the model will not be correct, the estimate of the parameter β_1, which is of interest here, should be approximately correct.

The negative binomial model provided a reasonable fit to the catches from both surveys. Results of the analysis for catch in numbers indicate that catches in the August survey are on average 13.5 times larger than catches in the September survey (Table 2). Results of the analysis for catch in mass indicate that catches in the August survey are 8.6 times larger catches in the September survey. The difference in results between the two analyses suggests that the August survey catches a disproportionately greater number of small hagfish compared to the September survey. Though mean catches in each stratum-year level were not strongly correlated between the two surveys, the estimated relative catchability factors appear to adequately adjust the catches from each survey to a common scale (Figure 10). There was a tendency for hagfish to be caught in the August survey but not in the September survey in certain strata and years.

With catch rates in the nGSL survey adjusted to equivalent catches in the sGSL, the distribution of hagfish throughout the Gulf of St. Lawrence was mapped for three-year blocks beginning in 1990. The density maps were produced via a delta-lognormal model, with interpolated densities generated in two steps. Presence-absence data were first estimated using a binomial Generalized Additive Model (GAM) with additive depth and spatial terms. Positive values were then fitted to a GAM, also with additive depth and spatial terms. Spatial prediction was achieved by combining the two model components (i.e. the probability of occurrence times the expected density). Catches were standardized to a common tow distance of 1.75 nautical miles) and night catches in the southern Gulf survey since 1992 were adjusted to daytime fishing.

The resulting maps show that Atlantic hagfish are present in the deep waters located along the edge of the sGSL survey area, occurring mainly in the estuary and the deeper portions of the Laurentian Channel (Figure 11). Prior to 2005 Atlantic hagfish also occurred in the Anticosti and Esquiman channels. Absence of hagfish in these channels since 2005 is unlikely to be an artifact of switching gear and vessel in the nGSL survey in 2005 because the vessel and gear used since then caught hagfish more often and in greater numbers compared to the former vessel and gear during comparative fishing (Bourdages et al. 2007). The apparent increase in the abundance and occurrence of Atlantic hagfish in the sGSL survey during the 1990s occurred in the northwestern part of the surveyed area (Figure 11).

SURVEY INDEX FOR ATLANTIC HAGFISH IN MANAGEMENT ZONE 4T9AB

For the period 1990 to 2015, between 8 and 24 trawl tows were conducted annually in the 4T9ab sector by the two surveys (Figure 12). The southern Gulf survey dominated sampling in 4T9ab, contributing at least twice as many tows yearly as the northern Gulf survey. The trawl survey index for 4T9ab fluctuated from year to year without a clear trend and with wide confidence limits around the annual mean catch (Figure 13a). The high 1990 value for the abundance index resulted from a single catch of over 100 hagfish, a level of catch that has not been observed in trawl surveys since 1990. The combined survey catches in 4T9ab were dominated by tows without any hagfish and their annual proportion appears to have peaked in the early 1990s and again in the 2009 and 2010 survey years (Figure 13b). The frequency of null catches contributed to the wide confidence intervals associated with most yearly mean catches in 4T9ab, but the time series of trawl survey abundance in 4T9ab, excluding null catches, continued to fluctuate widely without a clear trend (Figure 13c). The mean hagfish catch per tow for all surveys within the management zone is shown by horizontal dashed lines in Figures 13a and 13c. Mean catches over the past five survey years have been above or close to the long-term mean number of hagfish per tow, although the wide confidence intervals associated with larger hagfish catches have invariably encompassed the long-term average.

OTHER SOURCES OF RESEARCH DATA

Sentinel, snow crab and Cabot Strait surveys

The sGSL sentinel program was initiated in 1994 to evaluate the abundance of Atlantic cod during a moratorium initiated in 1993. Since 2003, the mobile gear sentinel program was revised to include a standardized trawl survey undertaken by four commercial trawlers each year, allocating fishing locations in the same strata shown in Figure 2. All vessels fish with a standard 300 Star Balloon otter trawl, fitted with a 40-mm codend liner. Tow speed and duration are 2.5 knots and 30 minutes. The vessels overlap in their coverage in order to compare and calibrate their catch rates. Eight vessels have participated in the survey since 2003 (Savoie 2012).

All catch data from the sentinel program (2003 to 2015) were examined. Unlike the RV survey time series presented here, Atlantic hagfish has never been caught in the mobile gear sentinel program. This was unexpected, as the sentinel program covers all the deep strata where hagfish are found in all of the annual RV surveys over the same period. Factors accounting for the absence of hagfish in the sentinel program are the survey gear and the fishing methodology. The RV survey has always towed the trawl at 3.5 knots and the codend was lined with a 6-mm mesh from 1971 to 1985 and 19 mm since 1986. It appears that the larger codend mesh liner used in the sentinel program, possibly combined with the slower tow speed, allow hagfish to escape capture. The trawl gear used in the sentinel program catches other small-bodied fishes; however, these species are less vigorous than hagfish and more frequently dead when brought to the surface, thus less likely to escape in the sentinel trawl.

The snow crab trawl survey has been conducted yearly since 1988 in snow crab management areas of the sGSL, with an increase in coverage to deeper areas of the Laurentian Chanel in 1997 (Moriyasu et al. 2008). Since 1997, the southern Gulf RV survey and the snow crab survey provide similar coverage with respect to Atlantic hagfish distribution, although the RV survey extends further northward and deeper in stratum 415 (Figure 2) than the snow crab survey (see Figure 2 in Benoît 2012). The snow crab survey is conducted with a Bigouden Nephrops trawl with a 40-mm liner in the codend, towed at 2 knots for 5 min. The snow crab survey has recorded the capture of only one hagfish since 1988 (E. Wade, DFO Science, Moncton; *pers. comm.).* As with the sentinel program, the snow crab survey employs a codend mesh size and slow tow speed that may lead hagfish to escape.

Cabot Strait, located at the entry to the Gulf of St. Lawrence, is an important overwintering area for marine fishes. From 1994 to 1997, surveys were conducted there every January to improve knowledge of the winter distribution and relative abundance of groundfish in this area (Chouinard and Hurlbut 2011). The survey was conducted in 1994 with 70 stations using a stratified design, then with 104 to 164 stations in the remaining years using grid sampling. The survey vessel and trawl were changed in 1996 from the CCGS *Alfred Needler* and Western IIa trawl to the CCGS *Wilfred Templeman* and the Campelen 1800 shrimp trawl. The occurrence of hagfish increased with the use of the Campelen trawl and is reflected in a wider distribution of hagfish after 1995 (Chouinard and Hurlbut 2011). Mean catch and weight is estimated at a highest level in 1997 at approximately 14 hagfish per standard tow and 0.71 kg/tow. This is lower than most annual mean catches of hagfish in the nGSL survey since the Campelen came into use in 2004 (Figure 9). Chouinard and Hurlbut (2011) concluded that hagfish were caught in the January surveys at low abundance in depths greater than 200 m with a relatively continuous distribution.

1992 Gulf Atlantic hagfish trap survey

In 1991, exploratory fishing for Atlantic hagfish was undertaken in the western portion of the Gulf of St. Lawrence and efforts were made to secure a market for the resource. This was undertaken in response to interest expressed by fishermen in the Gaspé region. Two boats fished the area using Korean baited traps, which resulted in large catches of hagfish, frequently filling the traps to capacity. In 1992, a more elaborate program was designed to cover a larger area (Figure 14), with a sampling protocol that intended to produce more background data on the abundance of the resource, their size distribution and the appropriate escapement size that the fishery should adopt. Two vessels that had participated in the fishery in 1991 were used in the 1992 program, the *Roitelet* and the *SeaStormer*.

The sampling program was unique in the degree of effort expended (a relatively fine spatial scale and a high number of traps deployed).The area was divided into 255 blocks (or sites) determined by 5’ latitude by 10’ longitude (roughly 9.3 x 12 km, Figure 14). Both vessels distributed their fishing effort throughout the survey area, the *Roitelet* fishing at 124 sites and the *SeaStormer* at 125; the remaining six sites were never sampled. At each site, a line was set with 35 traps, spaced 42 m apart. The traps fished for 2-3 hours during daytime. Each boat fished for 21 days, frequently completing six sites per day. The survey was conducted from July 16 to August 16, 1992.

The traps used for this survey were scaled down to 5-gallon plastic pails (22.7 L). This reduced trap size and short soak time were part of a sampling strategy used to assess the abundance and distribution of the hagfish resource over the largest area possible in the shortest timeframe. An entry funnel was set at one end of each trap and 154 holes were drilled in the sides and covers (¼ inch or 6.4 mm in diameter).

To characterize the size composition, the catches of three pails were combined from each station. If the hagfish catch was fewer than 200, all fish were measured. For larger catches, at least 200 hagfish were drawn randomly from the catch and measured. The hagfish catches were placed on ice and measurements were made later in the day or on the following day. In all, over 10,000 hagfish were measured (to the nearest 0.5 cm) in the survey.

At two sites in the 1992 survey, trap selectivity was tested by varying the diameter of escapement holes (6.4, 12.7, 15.9, 19.0 and 22.2 mm). No hagfish were captured with escapement holes of 15.9 mm and greater in their study. SENPAQ (1992) reported a minimum commercial size of 30 cm, for which a significant reduction in undersized hagfish was obtained with escapement holes of 12.7 mm diameter. However, they failed to catch fish greater than the minimum market size 80 g or 43 cm (reported in 2014) with any of the gear that they tested.

The highest densities of hagfish in the SENPAQ survey were found in the western portion of the Laurentian channel, and the lowest densities in the Anticosti channel (Figure 14), consistent with the results of the August trawl survey. However, the program had three problems that limit the inferences that can be drawn. First, one vessel broke the sampling protocol for estimating the number and weight of catches. The *SeaStormer* visually or volumetrically estimated the number of hagfish (presumably beyond a certain level of catch that could be easily counted). The catch weight was then derived from the estimated number of fish in each trap, applying a ratio of weight per number. This ratio was established from one counted and weighed sample per day. Second, there are anomalies in the catch data and indications of a very significant "vessel effect". Throughout the study, the *Roitelet* sustained persistent loss or breakage of traps (40% of all catches were reported as missing). Trap loss on the *SeaStormer* accounted for 2% of all the deployed traps. The *Roitelet* also recorded a higher proportion of null catches (Figure 15) and the mean catch of hagfish by the *Roitelet* was half (25 fish per trap) that of the *SeaStormer* (50 fish per trap). Third, catch and effort data from this study originate from archived spreadsheets. The raw data forms from this study have been lost or misplaced, making it impossible to verify or validate questionable information. The most critical missing information from this study is the length frequencies of hagfish.

The data from the SENPAQ survey were used to simulate different sampling schemes to identify optimal designs for future hagfish surveys. Only the catch rates (number of hagfish per trap) of the *SeaStormer* are considered, because this vessel had nearly complete sampling at each site. The *SeaStormer* fished at 125 sites, with a minimum of 30 and usually 35 successfully fished traps.

First, we randomly sampled 25, 20, 15 and 10 traps from the original data at each site to determine how trap density affects the precision of catch estimates. This was repeated 40 times at each level of selection. For each random selection, the mean catch per trap at each site and replication was first calculated, then the mean catch, the coefficient of variation (CV) and 95% confidence limits of the mean and cv were calculated at each replication across all sites (the survey mean). Lastly, the mean values across the 40 replications were computed for mean abundance, the cv and the upper and lower confidence limits. The mean catch varied little with reduced numbers of traps (not shown). The coefficient of variation of the estimate was high (around 100%) in all cases (Figure 16). A decrease in trap density from 35 to 10 per site resulted only in 4% increase in CV, though the increase in CV is accelerating with decreases in trap density as expected from the expected asymptotic relationship between sample size and precision.

Another simulation was conducted to evaluate the consequences of varying the number of sampling sites for a fixed trap density per site. From an initial sampling at 125 sites, 20 traps were randomly selected from 125, 100, 75, 50 and 25 sites. It appears that the confidence limits of estimated cv were particularly wide at 50 and 25 sampled sites and that the most prudent level of sampling would be to maintain at least 75 to 100 sampling sites for the area surveyed by the *SeaStormer.*

Reducing the number of traps deployed from 35 to 20 might increase the number of sites sampled per day, although the transit time between sites would increase. If more than six sites could be sampled per boat in one day, a survey with 90 sites might be accomplished within a week by two boats. Additional gains in efficiency might be obtained by allocating sampling sites proportionately to depth strata.

GENERAL OVERVIEW OF SURVEY DATA

Several reports recognize that monitoring hagfish abundance and size composition during exploitation is required (NEFSC 2003; DFO 2009a, 2009b). However, fisheries targeting hagfish tend to evolve from a small number of participants in restricted areas, so it may be difficult to justify committed resources for targeted surveys. With few participants in the fishery and limited profit margins from hagfish catches, industry-financed abundance surveys may not be feasible in some cases. Most ongoing hagfish fisheries lack an independent research survey, although almost all have conducted trap surveys of variable duration (e.g. one year in NAFO 4Vn by Mugridge et al. 2006a, 2006b; four years in NAFO 3Ps by Grant et al. 2009). In the absence of survey data, the catch rates and size composition of commercial gear are usually monitored. Commercial catch rates often do not provide a reliable (unbiased) index of abundance because harvesters tend to improve their gear and techniques and constantly seek fishing areas where they may maximize their catch rates (Hilborn and Walters 1992). Both sources of hagfish catch rates (hagfish surveys and commercial catch rates) invariably end once the fishery ceases, making it difficult to infer the time required by hagfish populations to recover from exploitation.

Throughout most of eastern Canada and the U.S., trawl surveys were established in the 1960s and 1970s to assess the relative abundance and characteristics of groundfish stocks and to characterize their environment. However, trawl surveys are not equally effective for all demersal fishes. The burrowing and sedentary behaviour of hagfish are thought to cause severe underestimates by trawl surveys or by visual surveys (Wakefield 1990). NEFSC (2003) presented groundfish trawl data for Atlantic hagfish from spring and fall surveys in the Gulf of Maine from the 1960s to 2002. Abundance indices varied widely from one year to the next, but trends were similar over time whether the survey was conducted in the spring or the autumn. The authors noted that hagfish were rare in their surveys and they questioned whether hagfish fluctuations were confounded by noise resulting from small sample sizes.

The southern Gulf RV trawl survey indicates that Atlantic hagfish abundance in the sGSL increased in the late 1990s and has fluctuated since 1998 at a higher level than was observed from 1971 to the mid-1990s (Figure 3). Similar patterns appear in the trend for hagfish occurrence. These trends cannot be attributed to changes in the research vessel and trawl, as the increasing pattern occurred well after the main vessel-trawl conversion was made in 1985. It is also not clear whether large inter-annual variations in abundance were related to variations in sampling intensity. The RV survey time series contributes information on large-scale population trends and the habitat occupied by Atlantic hagfish. For example, it appears that in the absence of any significant direct or indirect fishing effort on hagfish, their abundance has varied at least three to fourfold over the 45-year period that they were surveyed in the sGSL (discounting periods of no catch).

The northern Gulf RV survey covers a wider range of Atlantic hagfish in the GSL, but the time series begins in 1990. The abundance index of the northern Gulf survey, unlike the southern Gulf survey, shows no clear trend.

The combined abundance index for the 4T9ab management zone fluctuates without a clear trend and has wide confidence limits around the mean annual catch. At best, this index will allow for the detection of large changes in abundance only, if it tracks abundance at all. The RV survey catches a small number of hagfish (rarely exceeding 100 fish per year), so the ability to discern changes in the length composition in the short term may also be limited. Lastly, the RV surveys in the GSL have never been used to characterize the sex ratio and maturity state of hagfish. Bottom trawls may be more appropriate for obtaining maturity data than other trap sampling gear. Patzner (1998) noted that female hagfish with ripe eggs and male hagfish with more than small amounts of ripe sperm were rarely caught in baited traps, suggesting that this may be because spawning hagfish stop eating, thus becoming less vulnerable to capture in baited traps.

The approach used to develop a fishery for Pacific hagfish (*Eptatretus stoutii*) in British Columbia (B.C.) offers one alternative to resolve the need to monitor hagfish abundance through directed research surveys and/or commercial catch rates. Leask and Beamish (1999) reviewed the Pacific hagfish fishery that began in 1988 and that terminated in 1992 due to market conditions. A sporadic sampling program and poor understanding of Pacific hagfish biology made it difficult to assess the impacts of the fishery. They proposed that any future hagfish fishery be developed in a limited and closely monitored fashion to acquire information needed to assess impacts. Recognizing that limited knowledge of hagfish biology and life history would make it unlikely that Science could assess sustainable removal levels, Leask and

Beamish (1999) recommended management strategies intended to be both adaptive and realistic. A balance was required between the effort and resources used to monitor fishing and those used to improve understanding of the species.

The B.C. Pacific hagfish fishery that emerged in 2000 and 2001 was small scale and experimental, involving one vessel licensed to exploit two designated areas (Benson et al. 2001). In the same areas, an experimental fishery using 5-gallon baited pails was established with monthly sampling to collect biological data and to detect any seasonal migrations of hagfish. Some fishing was also authorized with Korean traps for biological samples and to provide catch rates consistent with the 1988 to 1992 fishery. There were no significant changes in catch rate or length composition over the 2000 to 2001 fishery, nor in comparison to the 1988 to 992 fishery. Benson et al. (2001) recommended that managers continue to limit the fishery to the two designated areas until more biological information could be incorporated into the assessment, that year-round fishing be conducted to improve information on seasonal movements, and that improvements be made to biological sampling.

The B.C. Pacific hagfish exploratory fishery was halted in 2002 with the withdrawal of the industry participant. Some unsuccessful attempts were made to renew the fishery during the 2000s, but since 2013 an exploratory fishery is conducted in three statistical areas using an adaptive management approach. Fishing effort is varied throughout the areas and two baited trap surveys (summer and winter) monitor the status of the hagfish resource (G.A. McFarlane, DFO Nanaimo, *pers. comm.*).

HAGFISH FISHERIES

Fisheries for hagfish have their origins in Korea and Japan, first as minor food fisheries, then as a source of soft leather in post-Second World War Japan (Honma 1998). By the early 1980s, “eelskins” manufactured in Korea from hagfish skins gained popularity. As reported by Martini and Flescher (2002), at the peak of the fishery in 1986 and 1987, a Korean fleet of over 1,000 vessels provided skins to roughly 100 processors. A similar domestic fishery existed in parts of Japan well before the Second World War, but expanded in response to the demand for hagfish skins (Gorbman et al. 1990). By 1987, Pacific hagfish were being fished off California (Martini and Flescher 2002) and a fishery began in late 1988 off British Columbia, (Neville and Beamish 1992). In 1989, Korean buyers expressed an interest in Atlantic hagfish off New England (Martini and Flescher 2002) and, in the same year, 125 tonnes were landed by Canadian boats in NAFO Div. 4X (Figure 17).

The Canadian fishery remained centred in NAFO Div. 4X through the 1990s, expanding eastward since 2000 (Rowe et al. 2009). Figure 17 illustrates the increase in landings since 2000 on the East Coast, part of which is due to an expansion of hagfish fishery locations. There are relatively few NAFO divisions below the Grand Banks where fisheries for Atlantic hagfish have not been attempted. Despite the apparent growth of the hagfish fishery in eastern Canada, it remains a specialized activity. In some NAFO divisions, as in 3Ps (Grant and Sullivan 2013), a single vessel has been active through most of the recent fishery. The 4T exploratory fishery has had four licensed vessels since 2011, but with only one vessel active each year.

Some variations in reported landings by NAFO Division may result from at-sea discarding and other factors. Although there may be limited sorting of hagfish catches at sea, some discarding may occur when catches are spoiled or are composed of small fish. Onboard observers are important in estimating the frequency and amount of discarding. In fisheries where hagfish are preserved at sea using ice, the landed weight of hagfish takes into account the effect of water and ice. However, the amount of ice applied to the catch may vary with the distance from landing port and weather conditions, requiring appropriate adjustments to obtain accurate landed weights. It is uncertain at this time whether the information is available to make these adjustments to the landed weights.

Commercial catch and effort data were obtained from NAFO landing statistics (1960 to 1998) and DFO catch-effort data files obtained from the Gulf, Quebec, Maritimes and Newfoundland-Labrador regions. Table 3 summarizes basic information on active vessels, fishing trips, catches and sampling. Hagfish landings from NAFO Div. 4T9ab are not presented in the table due to privacy considerations when fewer than five harvesters are active in a localized fishery. Landings are shown as a ratio to the maximum catch recorded in the 2013 fishery. The 2012 and 2015 fisheries yielded landings over 90% the level recorded in 2013, despite a twofold variation in the number of trips (Table 3).

Observer coverage in the 4T9ab hagfish fishery failed to reach the minimum requirement of 20% of trips specified in the annual Conservation Harvest Plans. At the required level of coverage, at least one trip should have been covered in all years and two trips in 2012. Instead, only one trip was accompanied by an observer in 2012 and in 2013 (Table 3). Observer coverage is important to obtain information at the sub-trip level. For example, on the 2012 trip, the observer recorded catch information on 22 gear deployments over a two-day trip and measured the length composition of hagfish on five deployments (Figure 18). Observers also estimate the weight of discarded hagfish, validating the information provided by harvesters in their logbooks. Unfortunately, observers have yet to consistently record any information on the cause of discarding (e.g., spoiled catch or hagfish too small), nor any length frequency sampling of the discarded catches.

Dockside monitors contribute information on the size composition of the landed hagfish catches. One length-frequency sample was made by dockside monitors in 2014, but with fish measurement in inches. Two landed hagfish catches were sampled by dockside monitors in 2015 (Table 3; Figure 18).

Various minimum commercial sizes have been reported for Atlantic hagfish fisheries. SENPAQ (1992) reported that Atlantic hagfish were accepted by processors when greater than 30 cm; in the Gulf of Maine, the minimum commercial size went from 35 cm to 51 cm after two years of harvests totaling 1,600 tonnes (Martini et al. 1997b). In the Newfoundland fishery, 80 g is considered to be the minimum marketable weight (DFO 2009b), but Grant (2006) referred to this as the minimum size for consumption, the minimum size for leather production being 50 cm. As noted above, the main buyer for Atlantic hagfish from the sGSL reported a minimum weight of 80 g (R. Murphy of R & K Murphy Enterprises, Wedgeport, NS, pers. comm.). Based on the length-weight parameters inTable 1, an 80 g hagfish would be 41 cm on the Newfoundland Grand Bank, 43 to 44 cm in the Gulf of St. Lawrence, and 48 cm in the Gulf of Maine. For RV catches in the southern Gulf, hagfish 50 cm and greater are rare and hagfish greater than 43 cm compose roughly 7% of catches.

The limited sampling of hagfish in the sGSL fishery indicates that a considerable proportion of catches (21% to 74%) are composed of fish below the preferred minimum size of 43 cm (Figure 18). The size composition of hagfish catches ranged between 30 and 55 cm in 2012 and 2013. The lack of sufficient commercial-sized hagfish from the Gulf of St. Lawrence was a significant factor in the decision not to pursue the development of a commercial endeavor in the western part of the Gulf in the early 1990s (T. Hurlbut, formerly DFO Science, Moncton, pers. comm.).

Kept and discarded weights of hagfish were recorded in most logbooks in the 4Tab fishery. Annual total discards as a percentage of total catch ranged between 2% and 13% (Table 3). The duration that baited barrels fish (trap soak time) may affect the frequency and amount of hagfish discarding. Trap soak times in the 4T9ab fishery ranged from 4 hours to 11 days and discarding ranged between 0 and 100% of hagfish catch weights (logbook data, 2011 to 2015; n = 70). Soak times exceeding 24 hours were associated with accumulating mucus in the traps, fish decomposition and skin damage caused by biting. Discarding tended to increase with increasing trap soak time (Figure 19). Discarding was also more prevalent with soak times > 24 hours. Of 45 catches made within 24 hours of soaking, discarding exceeded 10% of the catch for only 7 of the catches; of 25 catches made with soak times > 24 hours, 15 exceeded 10% discarding.

There is presently no information available on the size at which maturity occurs in hagfish of the sGSL. This information is important for the management of fish stocks. Fishery managers may restrict the capture of fish less than the body length at which 50% are mature (L50). Knowing L50 for a given species and stock, it is also possible to specify the fishing gear that should limit the capture of sizes less than L50, thus increasing the likelihood that fish will survive fishing to spawn at least once. L50 has been estimated for Atlantic hagfish populations on the southwest slope of the Newfoundland Grand Bank (NAFO Div. 3O; Grant 2006) and on the Scotian Shelf in NAFO Div. 4W (Mugridge et al. 2007). The same method was used to define female sexual maturity in the two populations. Mature female ovaries were defined by the presence of egg lengths of 14 mm or more or by the presence of brown bodies (degenerate or atretic eggs) and/or ovulated follicles, indicative of past reproduction. Based on this approach, L50 was identified as 38 cm for the SW Grand Bank population and 42.4 cm for the Scotian Shelf hagfish population.

MANAGEMENT APPROACHES OF ATLANTIC HAGFISH

The management approaches for Atlantic hagfish fisheries differ between DFO regions. Hagfish fisheries on the Scotian Shelf are well established and compose a large portion of East Coast harvests. The DFO Maritimes Region manages this fishery by input controls, with limits on the number of licences, vessel size, the number of traps per licence, and the size of trap escapement holes (S. Quigley, DFO Maritimes Region, pers. comm.) (Table 4). In 2014 and 2015, the Maritimes Region updated several management measures in consultation with their regional Hagfish Advisory Committee, composed of DFO Resource Management, Conservation and Protection Branch, and representatives of the fishing industry and First Nations. Table 4 summarizes the key management measures that were in effect in the most recent fisheries and updates the information provided in the section on science and management strategies in the DFO (2009b) proceedings report of the 2007 interregional workshop on Atlantic hagfish.

Atlantic hagfish in the Newfoundland-Labrador Region have been exploited from 2004 to 2008 in NAFO Div. 3O and from 2005 to 2013 in NAFO Div. 3Ps (DFO 2009b). DFO Science does not provide advice to resource managers for this species; that role is provided by the Centre for Sustainable Aquatic Resources, Fisheries and Marine Institute of Memorial University of Newfoundland. This is the only region that has imposed a TAC on Atlantic hagfish in each NAFO division. Designated sectors for fishing hagfish were established based on the knowledge of harvesters in the monkfish gillnet fishery, resulting in 10 blocks (each block is 10’ latitude by 10’ longitude) in NAFO Div. 3O and 7 blocks (including one 10’x4’ block) in NAFO Div. 3Ps. The 3Ps fishery has been managed with a 181 t TAC, but with an additional limit to removals within any single block of 45.4 t. No license applications were made for the 3Ps exploratory fishery in 2014 and 2015.

The TACs on Atlantic hagfish in NAFO Divs. 3O and 3Ps were initially established through industry consultations and were considered to be reasonable amounts to store and market (Grant et al. 2009). The most recent update on the 3Ps hagfish fishery indicates that, after seven years of fishing, catch rates are in decline and the proportion of mature females

(> 44 cm) is reduced in all depth strata where hagfish have been fished (Grant and Sullivan 2013). Those results indicate that the fishing pressure on the stock may be too high.

The Gulf Region approached the management of the exploratory hagfish fishery in NAFO Div. 4T in a manner consistent with the Maritimes Region. Some gear conditions (number of traps, configuration of entrance and escape holes) were similar to those in effect in the Maritimes Region, or were developed in consultation with harvesters. Gulf Region managers imposed a fishing area (4T9ab, Figure 2) and a participation clause, aimed at encouraging engaged participants in the fishery. The participation clause used in the 2011 and 2012 fisheries required each of the four license holders to fish a minimum of 10 documented fishing trips with catches or landings of Atlantic hagfish. For the 2013 fishery, the requirement was reduced to five trips.

SOURCES OF UNCERTAINTY

Although the biology of Atlantic hagfish has several characteristics of slow growing, long lived fishes, there is no known method for determining the age of hagfish. As a result, it is impossible to know with any certainty the stock age structure, growth rate, total mortality, or age at reproduction. There is therefore little information to determine the productivity of hagfish populations and therefore their potential for sustainable exploitation.

There is no information on the stock structure of Atlantic hagfish. Annual trawl surveys provide long-term coarse trends in abundance, but the catchability of hagfish to trawling gear is low. There is uncertainty in the ability of these surveys to track changes in abundance and size structure of hagfish in areas where they are exploited.

Discarding, reported in harvester logbooks, may exceed 10% of the weight of hagfish catches. Though there appears to be a relationship between soak time and the extent of discarding, some uncertainty remains concerning the causes of discarding and their potential effect. The survival of discarded hagfish is probably very low when the catch is spoiled; however, survival may be high if hagfish are released live from traps (Benoît et al. 2013).

RECOMMENDATIONS

This report has identified a number of knowledge gaps, some that may be attributed to the species, and others that are more specific to the exploratory fishery in 4T9ab. Many aspects of the biology of hagfish are poorly known and cannot be resolved within the scope of this fishery. However, it is uncertain whether sufficient information is available on stock abundance, size composition and level of fishery removals to assess the effects of fishing.

- Biological sampling on trawl surveys should be augmented and should include sex identification and reproductive staging to obtain annual sex ratios and size at reproduction.
- Trawl survey data may only track hagfish abundance and distribution in the long term or on a coarse spatial scale. If more precise data are required to support management, industry based trap surveys would be the best approach. Some work would be required to determine the parameters of such a survey.
- Information on the fishery originating from harvesters (logbooks), observers or dockside monitors needs to be transmitted to DFO and incorporated in the relevant databases in a timely manner.
- There is a need to review the size at 50% maturity of hagfish in the southern Gulf of St. Lawrence. The collection of biological information, particularly individual lengths and

determination of maturity, needs to follow standardized protocols consistent with methods used for other NW Atlantic stocks.

- There is a need to review fishing practices in the southern Gulf hagfish fishery, notably:
    - To identify soak times that reduce catch spoilage and discarding. Current fishing practices include very long soak times.
    - To ensure that the nominal size, number, and location of escape holes are optimal for the escapement of undersized hagfish. Current management measures in the southern Gulf impose a ½ inch minimum diameter hole size, a smaller size than is used in fisheries managed by DFO in the Newfoundland-Labrador and Maritimes regions.
    - Measures need to be in place to ensure that the number of barrels used is commensurate with the ability to tend the gear. Currently there are cases of long soak times due to harvesters not having the capacity to haul all of their gear in one trip.
    - There are reports of spoiled catches associated with high densities of amphipods (sand fleas), though it is not clear if the amphipods caused the spoilage or if they were drawn by it. Similar problems were experienced in the Newfoundland fishery. Documenting and then avoiding areas with high amphipod densities might improve catch quality and reduce discarding.
- There is a nominal requirement for observer coverage in this fishery (20%); however, that target was met in only one of the five years of this fishery, despite the harvesters complying with the hail-out provisions. Measures need to be put in place to ensure that the required number of trips is covered by observers, with a minimum of one trip covered per year. Observers provide data on a set-by-set basis, which is not possible from dockside monitoring; furthermore, observers can provide reliable information on the abundance and size composition of discarded catch.

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TABLES

Table 1. Length-weight relationships for Atlantic hagfish populations in the Northwest Atlantic based on the allometric relationship weight = a length^b. Sampled areas are the Grand Bank of Newfoundland (Grand Bank; Grant 2006, southwest Newfoundland (SW Nfld 2006; S.M. Grant, pers. comm.), northern Gulf of St. Lawrence RV survey 2003 to 2009 (Bourdages and Ouellet 2011), the 1992 southern Gulf of St. Lawrence trap survey (SENPAQ 1992), the southern Gulf of St. Lawrence from RV survey data (this report), and the Gulf of Maine (NEFSC 2003). For Grand Bank data, the relationship is based on length in mm. All other relationships are based on length in cm and weight in grams.

Parameter	Grand Bank	SW Nfld 2006	N. Gulf RV	S. Gulf 1992	S. Gulf RV	Gulf of Maine
a	0.000011	0.0059	0.0024	0.0026	0.0040	0.0040
b	2.627	2.532	2.798	2.7580	2.5537	2.5571
R^2	0.91	0.84	0.80	na	na	0.82
Sample size	1,785	889	908	na	808	49

Table 2. Results of the negative binomial mixed effects modelling for catches of hagfish in numbers and mass.

Unit	Parameter	Estimate	Standard error	P-value
Numbers (N_{obs}=819, N_s=75)	Intercept (β_0)	3.0870	0.0042	< 0.001
	Survey (β_1)	-2.6438	0.0042	< 0.001
	Random effect (δ_s)	0.3655	na	na
	Residual error	0.9062	na	na
Mass (N_{obs}=819, N_s=75)	Intercept (β_0)	0.2189	0.0022	< 0.001
	Survey (β_1)	-2.7556	0.0022	< 0.001
	Random effect (δ_s)	0.3470	na	na
	Residual error	0.8277	na	na

Table 3. Fishing activity and sampling in the 4T9ab hagfish fishery, including the number of active participants, the number of fishing trips and an index of landings relative to the highest level in 2013. Four participants were licensed each year in this fishery. Discarding percentage is based on estimated catches from logbooks. Also indicated are the number of fishing trips accompanied by observers and length samples recorded by observers and dockside monitors (DM).

Year	Active participants	Vessel trips	Landings ratio	% discards	Observer trips	Observer samples	DM samples
2011	1	9	0.13	4.0	0	0	0
2012	3	12	0.98	9.7	1	5	0
2013	1	6	1.00	13.2	1	1	0
2014	1	5	0.41	15.4	0	0	1
2015	1	6	0.92	4.3	0	0	2

Table 4. Comparison of recent management measures for Atlantic hagfish fisheries, by DFO region. The Newfoundland-Labrador (N-L) Region had no fishery in 2014 and 2015. Measures shown were effective in 2013 in the N-L Region and in 2015 in the Maritimes and Gulf regions.

Comparison	N-L Region	Maritimes Region	Gulf Region
Type of licence	Exploratory	Commercial	Exploratory
Hail in / Hail out	100%	100%	100%
Dockside monitoring	100%	100%	100%
Observer coverage	100% + biologist on some trips	Target 1 trip / licence /season	20%
VMS	Yes	Yes	No
Season	Sept – Nov (variable)	April 15 – Oct 15	Aug – Oct
Quota	NAFO 3Ps: 181 t.[1]	None	None
Authorized trap (barrel)	220 litres	Maximum 102.5 cm (H) x 61 cm (diam.)	114.3 cm (H) x 61 cm (diam.)
Maximum traps	200 per 24 hr	450	500
Entrance funnels[2]	Minimum 4	Maximum 4	Maximum 6
Escape holes (number; diameter)	115; 40% 9/16", 60% 19/32"	Minimum 36; 9/16"	Minimum 24; at least ½"
Minimum fish size	60 g, limited to 5% of total catch	None	None

[1] authorized fishing is in seven blocks (six blocks 10'x10' latitude & longitude; 1 block 10'x4'). The maximum authorized catch is no more than ¼ of the quota (45 t per block).
[2] at least one funnel attached with biodegradable material.

FIGURES

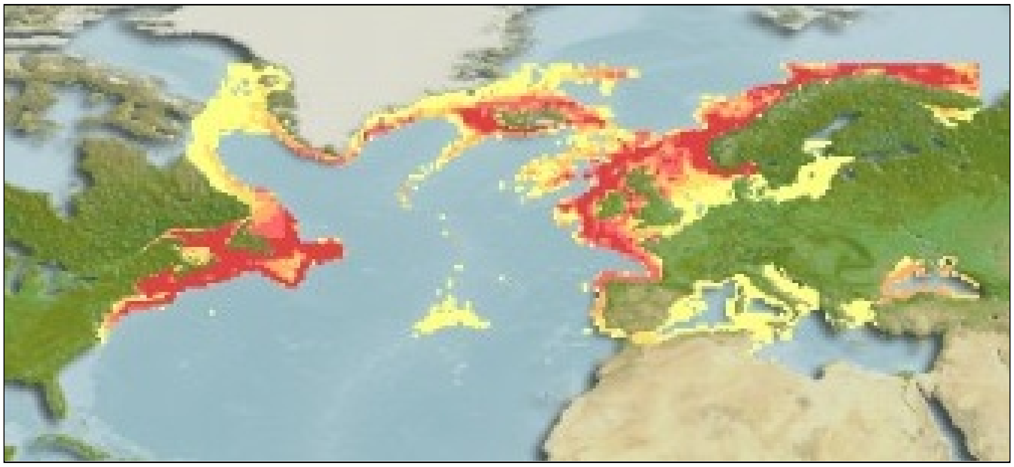

Figure 1. Map of the native range of Atlantic hagfish in the North Atlantic showing the relative probability of occurrence (yellow shading denotes lowest probability of occurrence; red shading denotes highest probability). The map was generated via www.aquamaps.org, version of Aug. 2013 (web accessed 30 Nov. 2015).

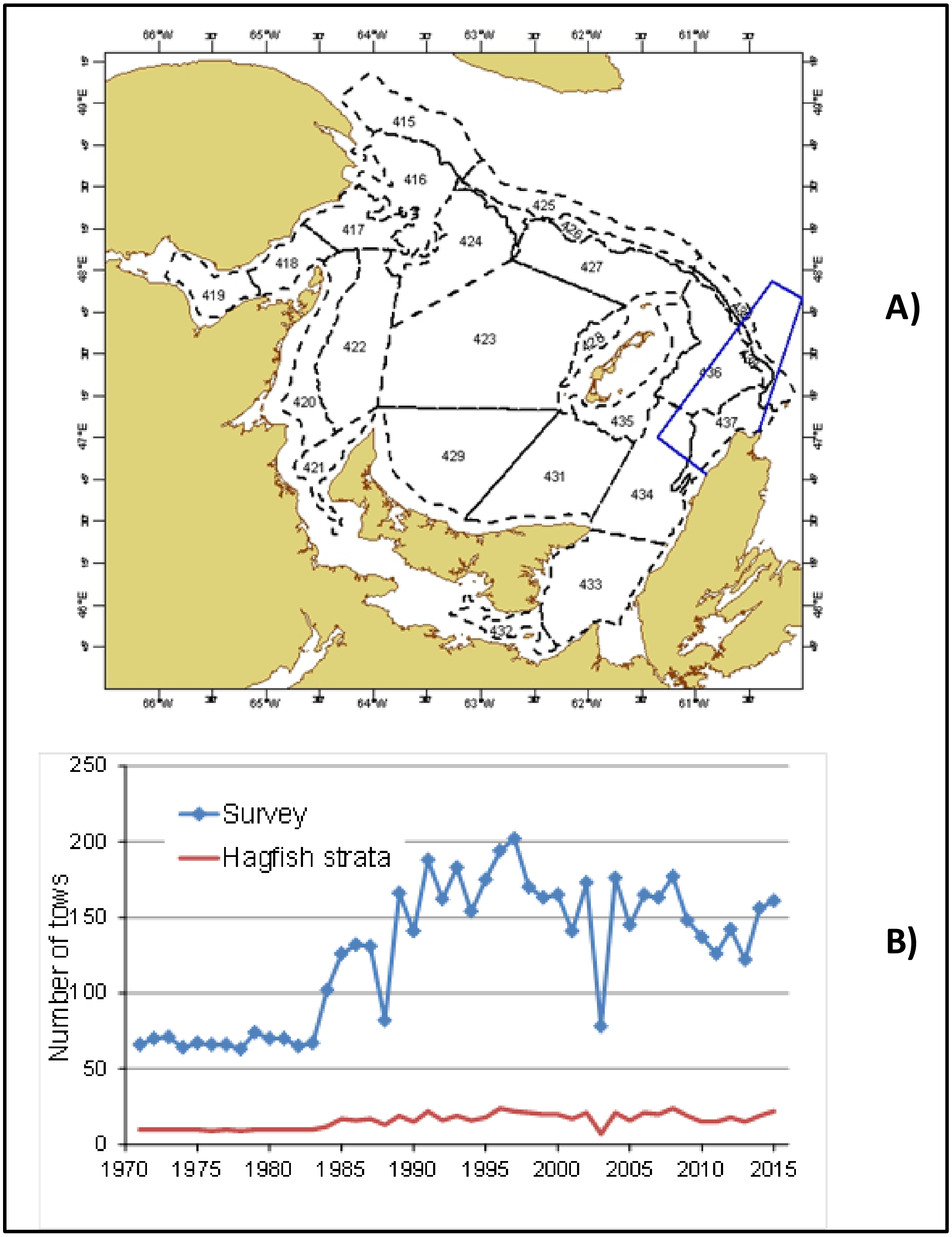

Figure 2. A) Map of the southern Gulf of St. Lawrence showing the area stratification used for sampling in the annual bottom trawl survey (dashed lines) and the management area (4T9ab) where Atlantic hagfish are exploited (solid lines). B) Annual total number of valid trawl tows in the survey since 1971 and the number of tows in strata 415, 425, 437 and 439 where 97% of all the Atlantic hagfish survey catches have been made.

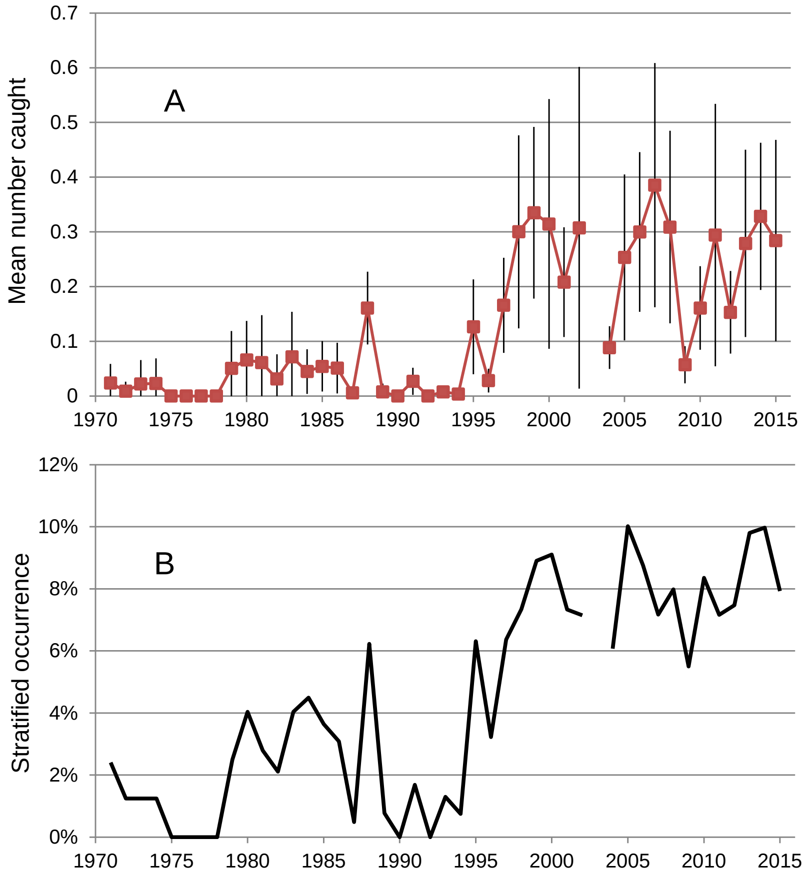

Figure 3. Indices of Atlantic hagfish abundance and distribution in the southern Gulf of St. Lawrence derived from the annual bottom trawl survey, 1971-2015. A) Stratified mean number per tow showing 95% confidence limits as vertical lines. B) The stratified percent occurrence of Atlantic hagfish.

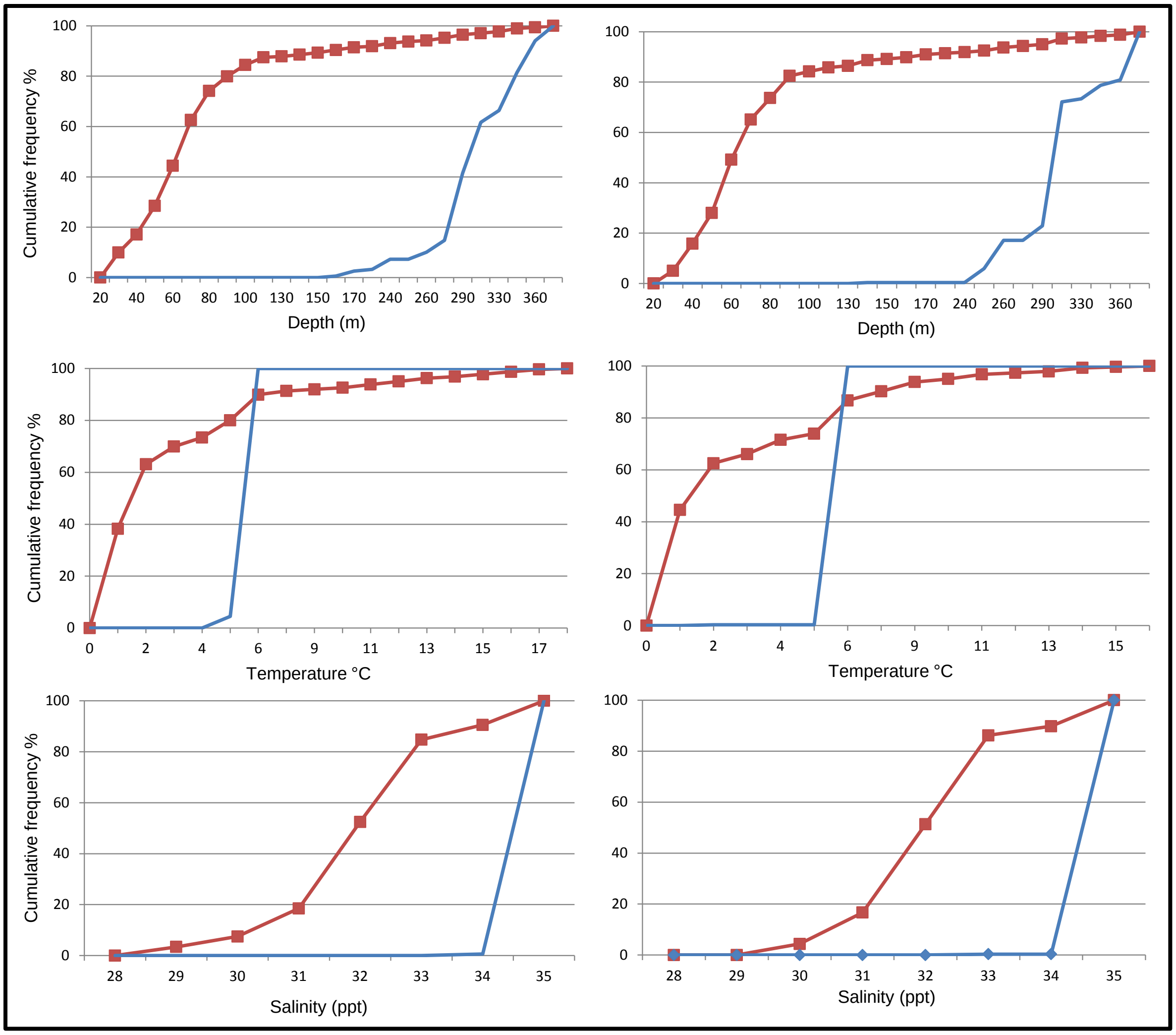

Figure 4. Cumulative density functions for sampled depth, temperature and salinity in the 2006 (graphs on left) and 2007 (graphs on right) trawl survey. The dotted lines show the cumulative percentage of the habitat variable that was sampled; the solid lines show the cumulative frequency of hagfish catch across the same range of sampling.

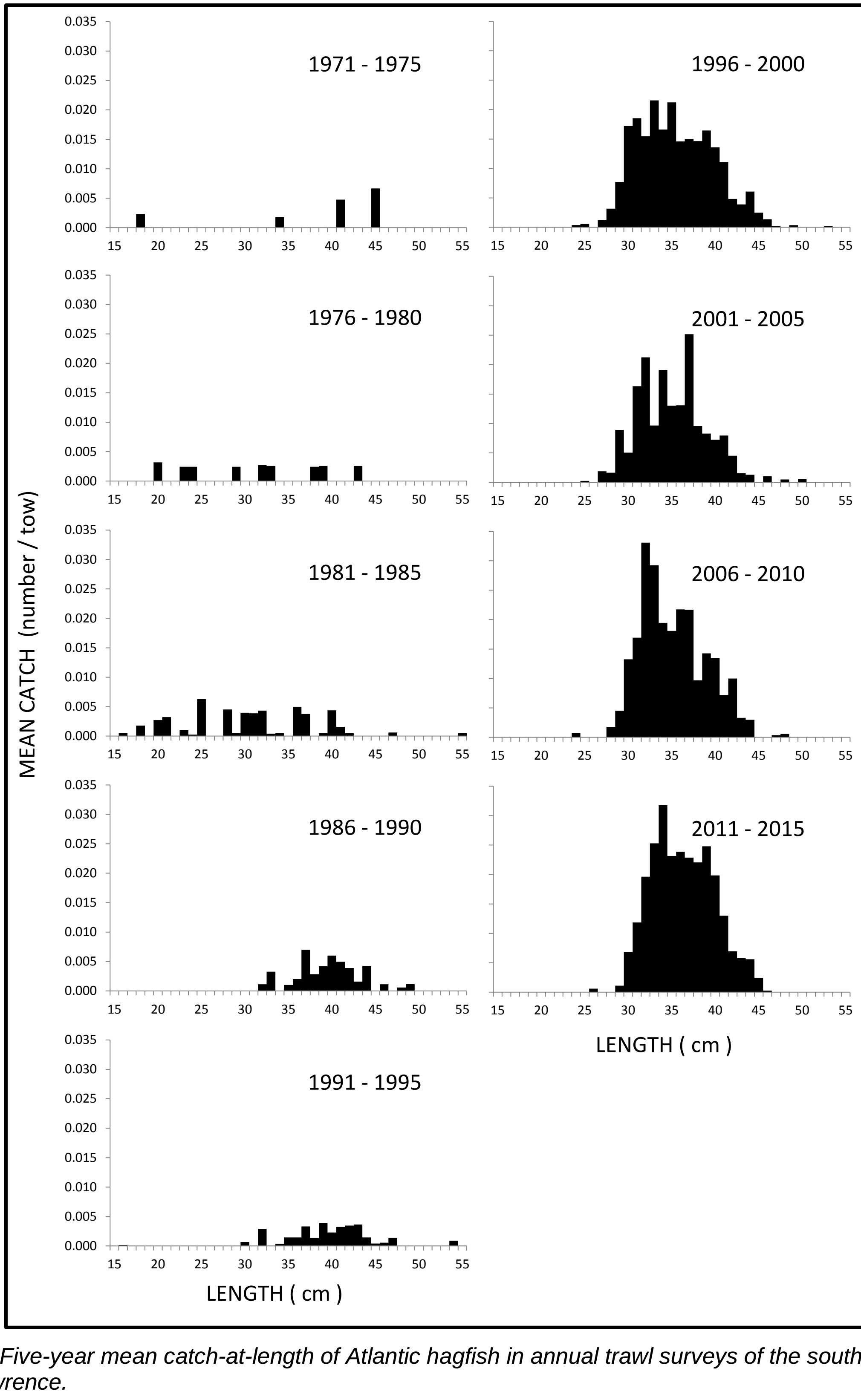

Figure 5. Five-year mean catch-at-length of Atlantic hagfish in annual trawl surveys of the southern Gulf of St. Lawrence.

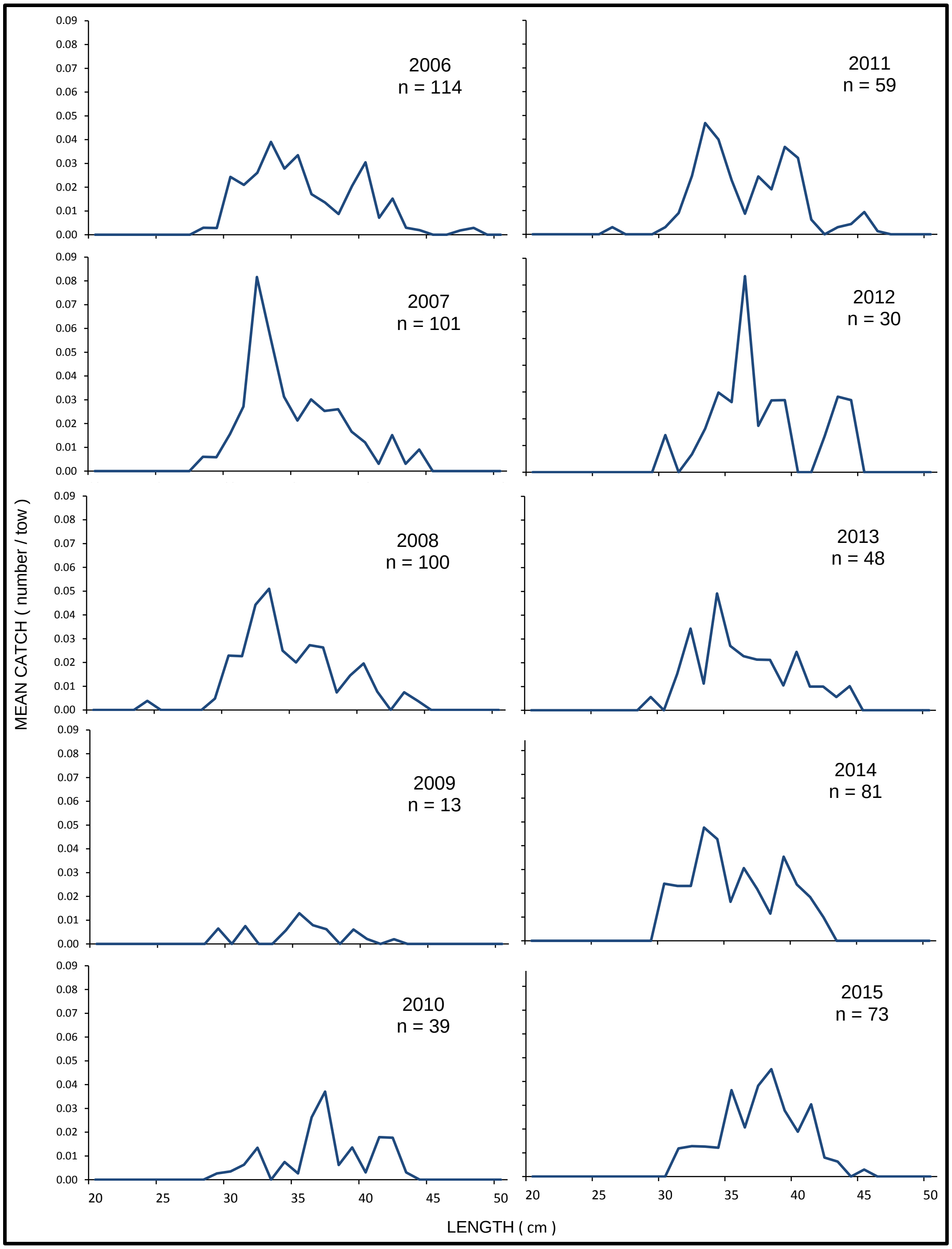

Figure 6. Atlantic hagfish length frequencies in the ten most recent annual trawl surveys in the southern Gulf of St. Lawrence, also indicating the number of hagfish (n) measured in each survey.

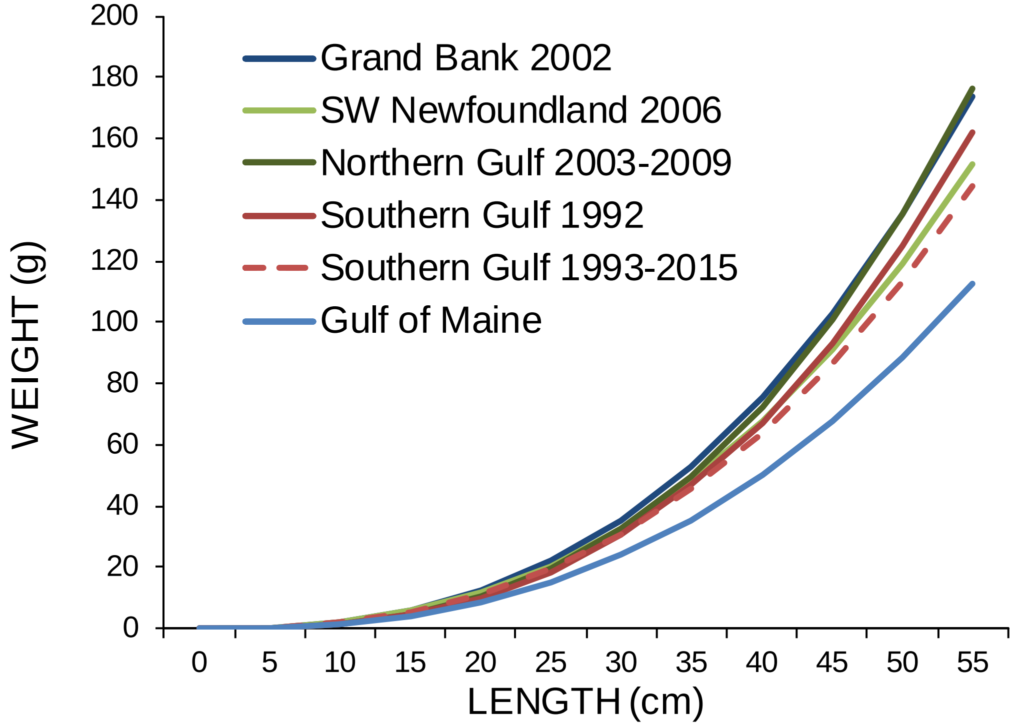

Figure 7. Length-weight relationships for various populations of Atlantic hagfish in the Northwest Atlantic, as referenced in Table 1.

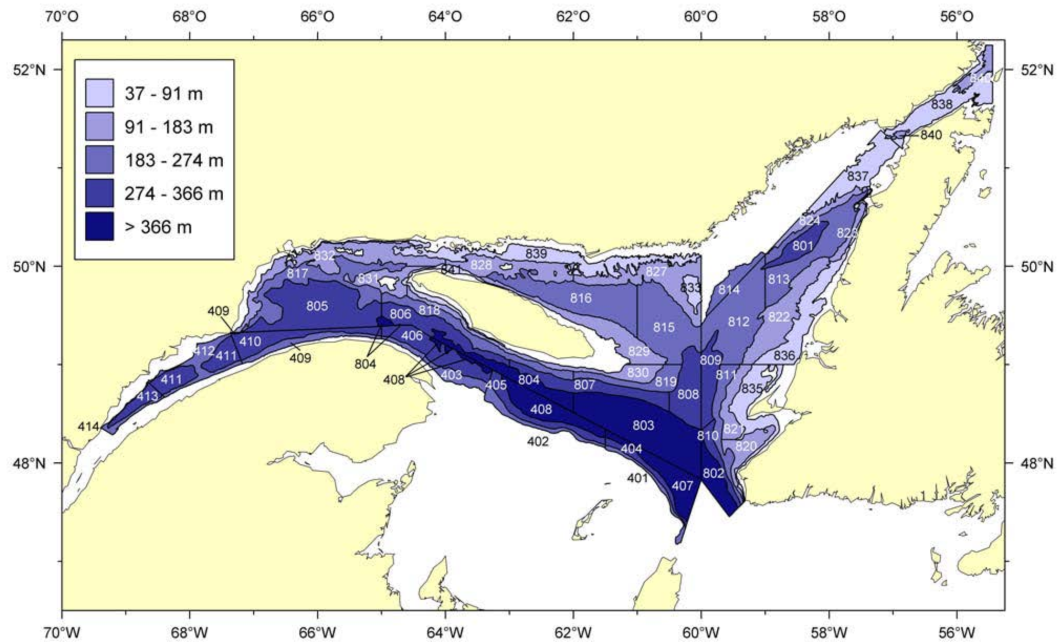

Figure 8. Area coverage of the northern Gulf of St. Lawrence trawl survey, showing depth stratification.

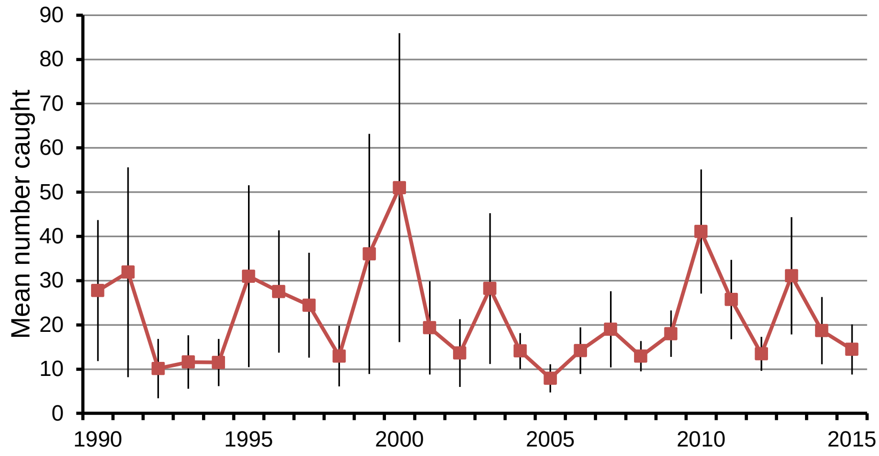

Figure 9. Mean stratified number per tow of Atlantic hagfish caught in the northern Gulf RV survey, showing 95% confidence limits as vertical lines.

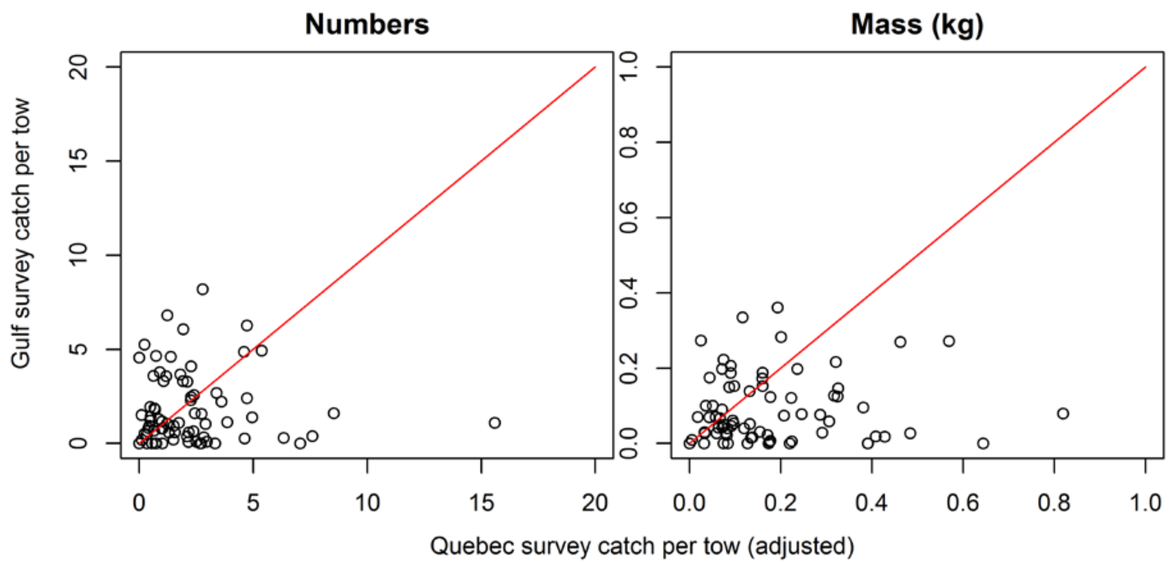

Figure 10. Bivariate plots of stratum-year mean survey catches in numbers (left panel) and mass (right panel) for adjusted Quebec survey catches and Gulf survey catches. Quebec survey catches were adjusted based on the results of the negative-binomial mixed effects modelling. The red line indicates a 1:1 relationship.

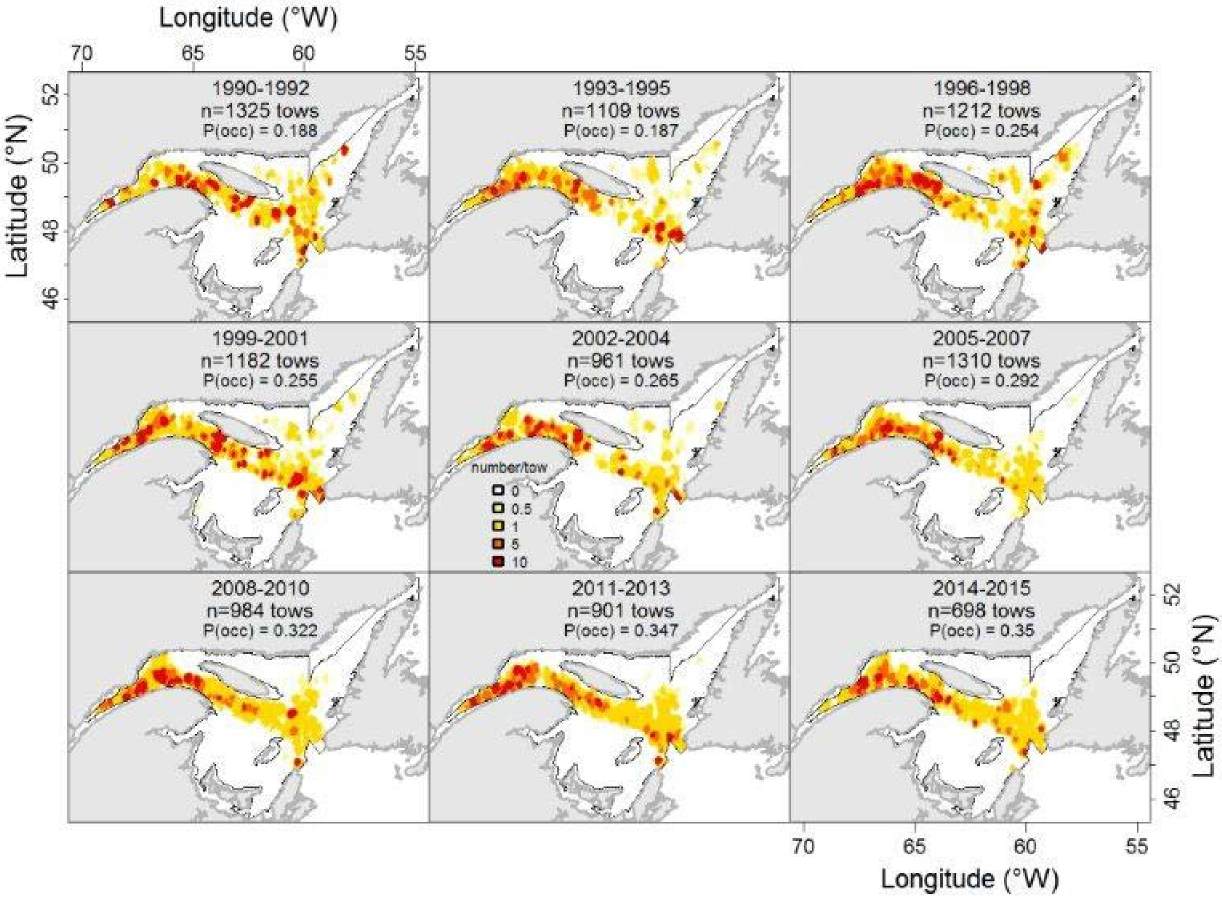

Figure 11. Density contours of Atlantic hagfish in surveys of the Gulf of St. Lawrence based on the number caught per standard tow in two or three-year blocks since 1990. All data have been standardized to equivalent catch efficiency with survey gear used in the southern Gulf.

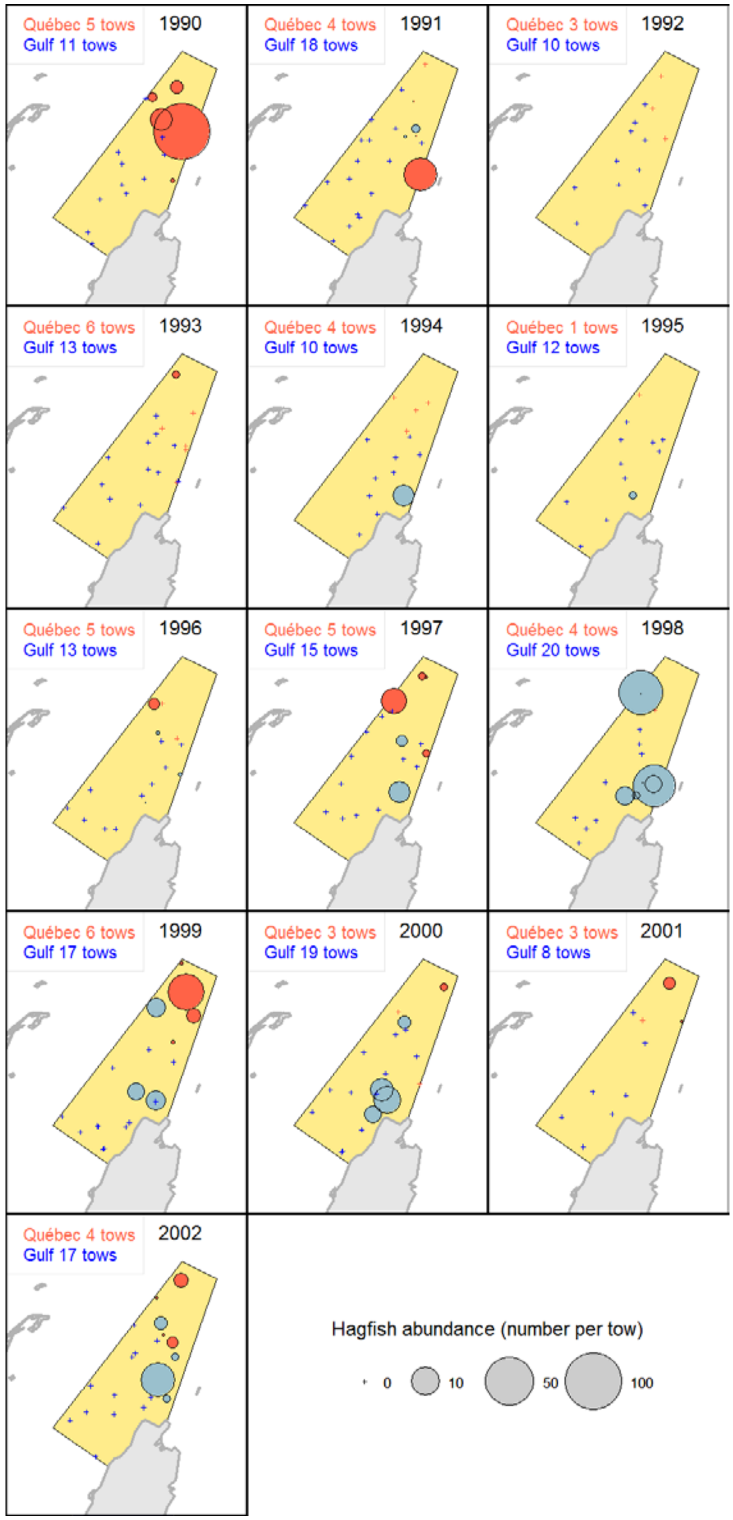

Figure 12. Maps of Atlantic hagfish catches in the management zone 4T9ab (yellow shaded area) off northern Cape Breton in the eastern Gulf of St. Lawrence, 1990 to 2002. Data points show hagfish catches for the northern Gulf survey undertaken by DFO's Quebec region (red symbols) calibrated to catches of hagfish in the southern Gulf survey undertake by DFO's Gulf region (blue symbols).

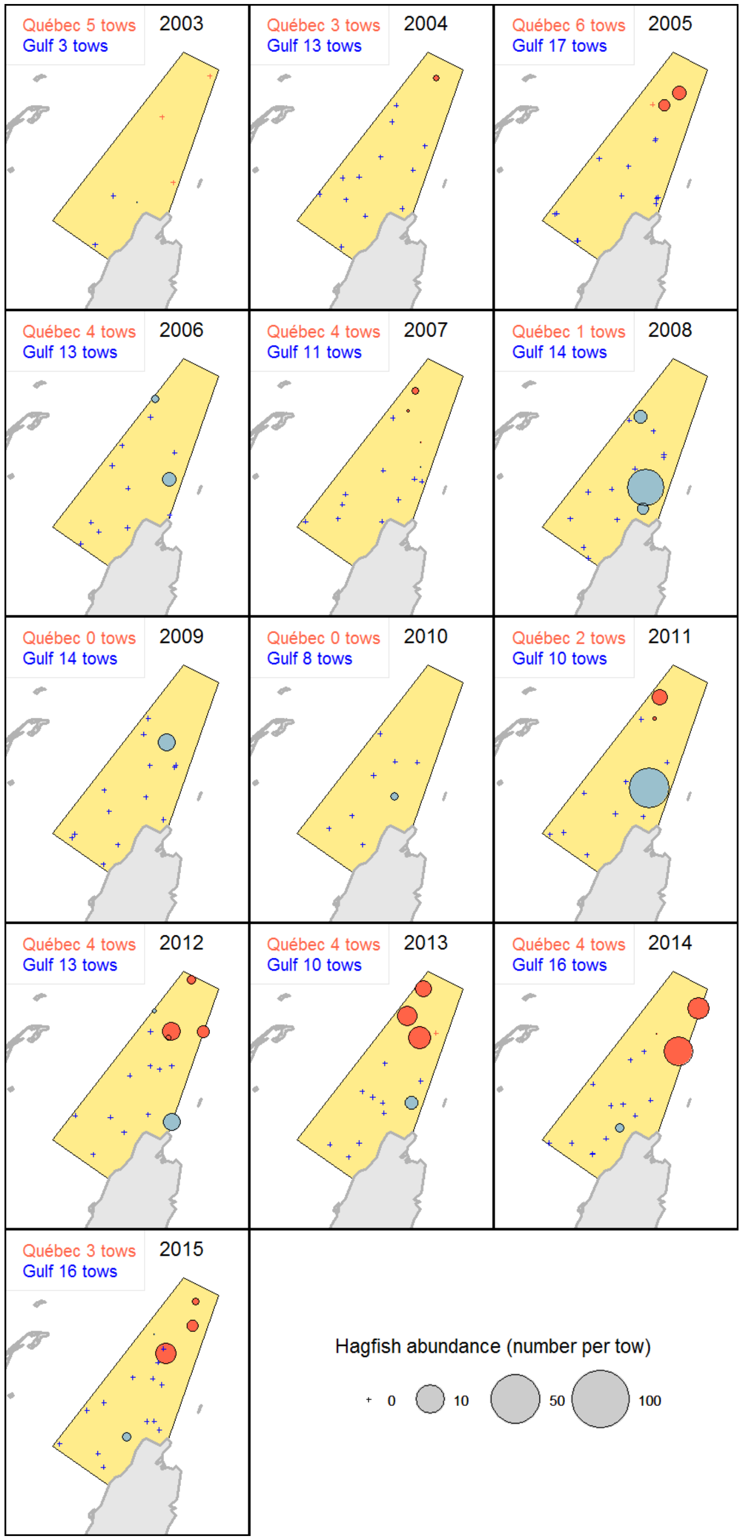

Figure 12 (continued). Maps of catches in the 2003 to 2015 surveys.

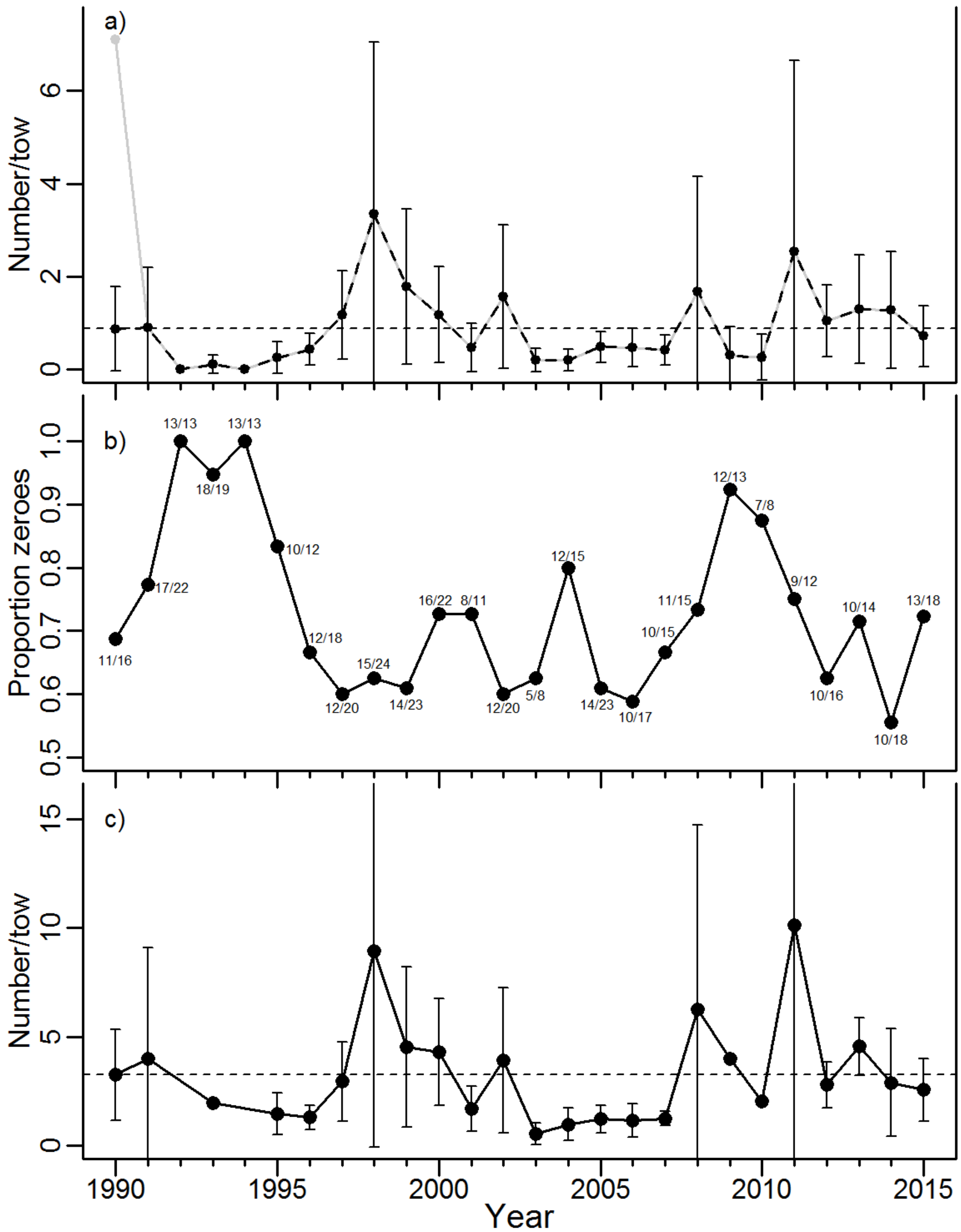

Figure 13. Index of hagfish abundance in the 4T9ab management area off northern Cape Breton from intercalibrated data of the northern and southern Gulf of St. Lawrence trawl surveys. Panel a) Mean numbers per tow, including zero catches. The dashed black line excludes a single high abundance tow conducted in 1990 and the gray line includes it. Black dots represent the mean catch in each year and the whiskers indicate the 95% confidence interval. The horizontal dashed line shows the long-term mean catch rate (years 1990 to 2015) in 4T9ab. Panel b) Proportion of tows with no Atlantic hagfish capture. The fraction of tows with zero catch appears adjacent to the dots. Panel c) Mean numbers per tow, excluding zero catches. Interpretation of symbols is similar to panel a.

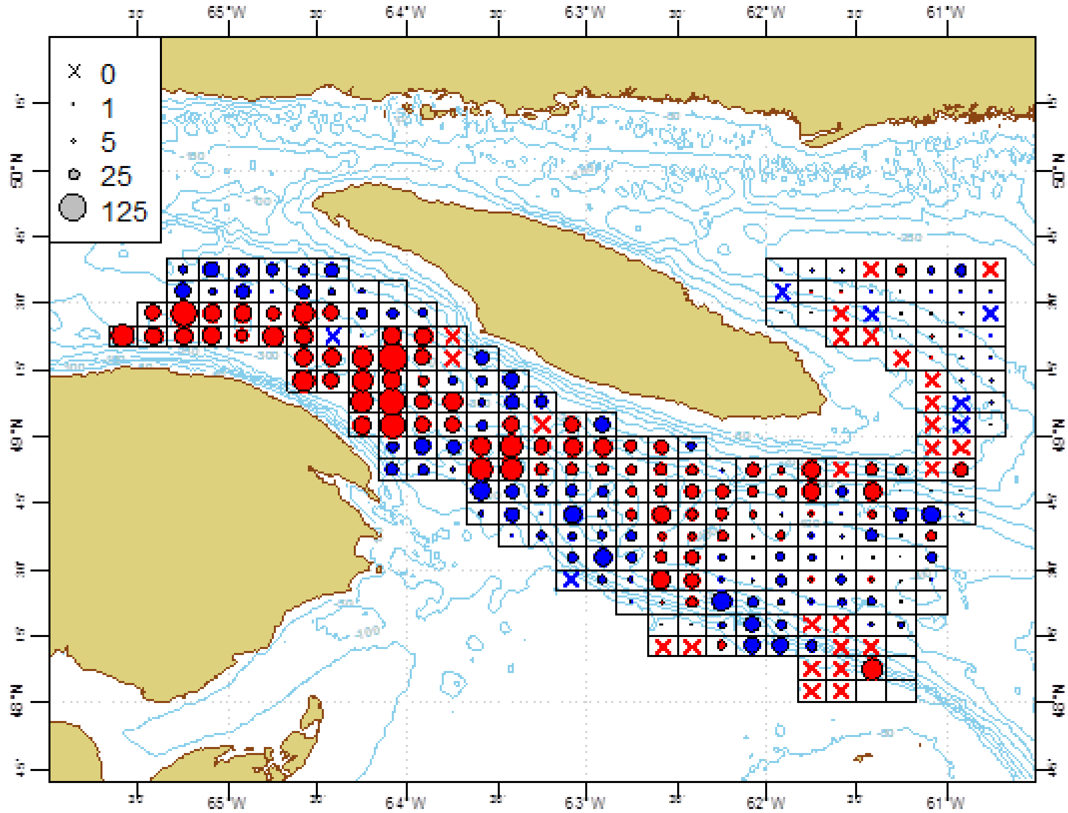

Figure 14. Area map of the western Gulf of St. Lawrence, showing the Gaspé Peninsula, Anticosti Island and the Quebec North Shore and the grid used during the 1992 Atlantic hagfish trap survey by SENPAQ (1992). Catch per unit effort (number per trap per 1-hour fishing time) are shown by symbol size (see legend) and by fishing boat (Roitelet as blue symbols; Sea Stormer as red symbols).

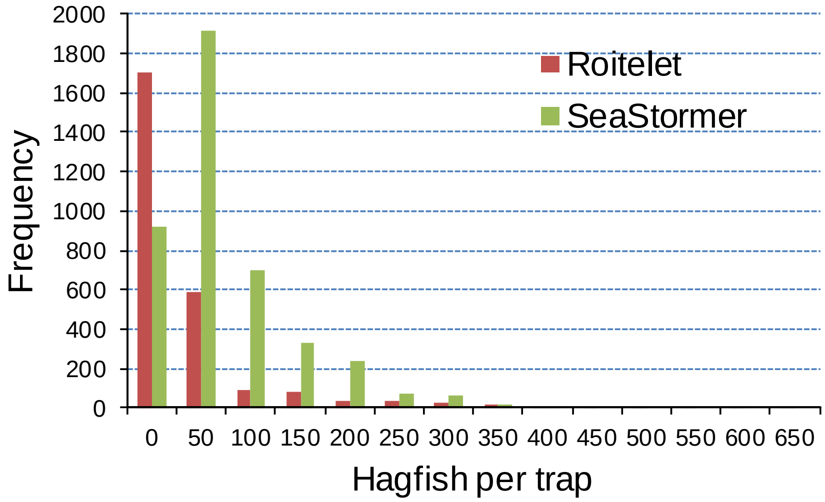

Figure 15. Frequency of Atlantic hagfish catches by the two fishing boats that participated in the 1992 hagfish trap survey in the Gulf of St. Lawrence.

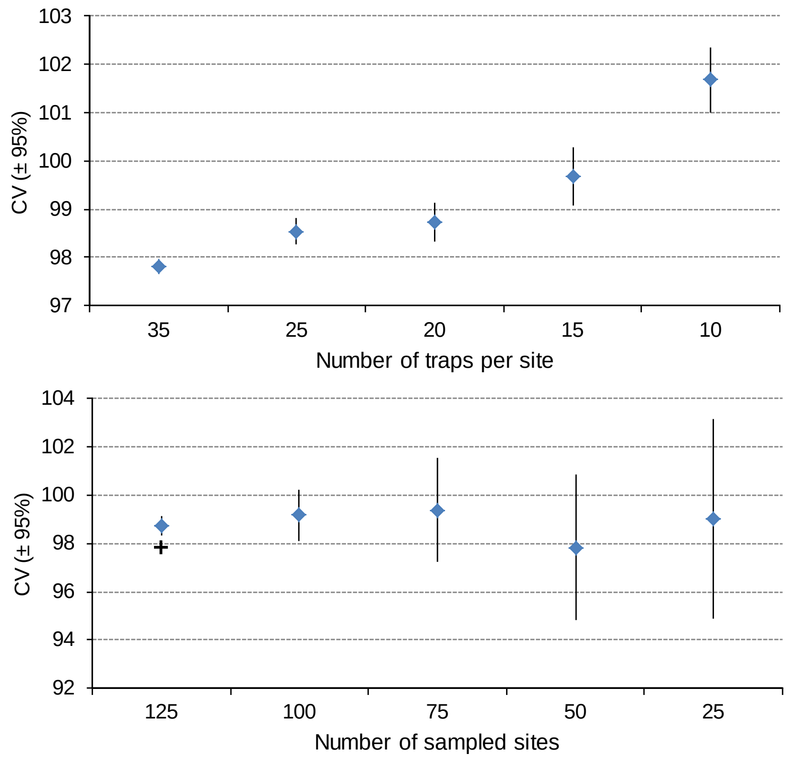

Figure 16. Results of simulations at varying sampling intensity, based on the reported catches of the vessel SeaStormer in the Gulf of St. Lawrence 1992 hagfish survey. The SeaStormer fished at 125 sites, deploying 32 to 35 traps successfully at each site. Upper graph shows the coefficient of variation (cv) and 95% confidence limits for 40 simulations of all sites sampled, decreasing the traps deployed. Lower graph shows the same parameters estimated with 40 simulations of 20 traps deployed at a decreasing number of sampled sites. The + symbol indicates the observed cv with full sampling (all traps and all sites).

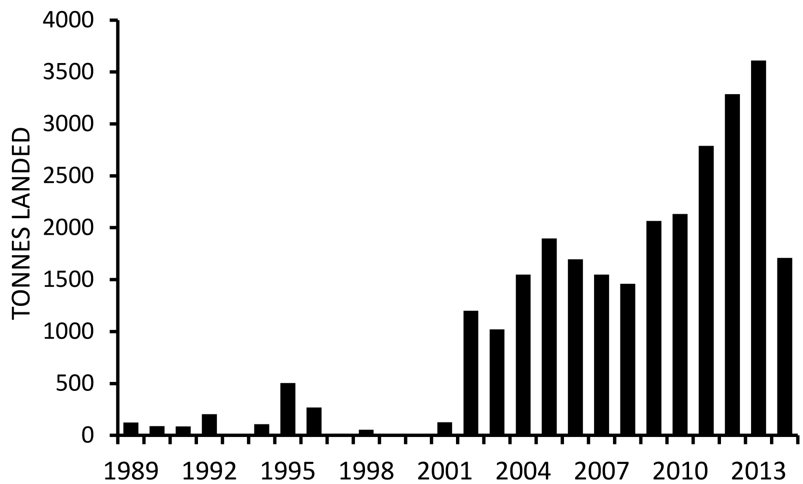

Figure 17. Landings of Atlantic hagfish by Canadian boats in fisheries of eastern Canada. Data unavailable for 2015.

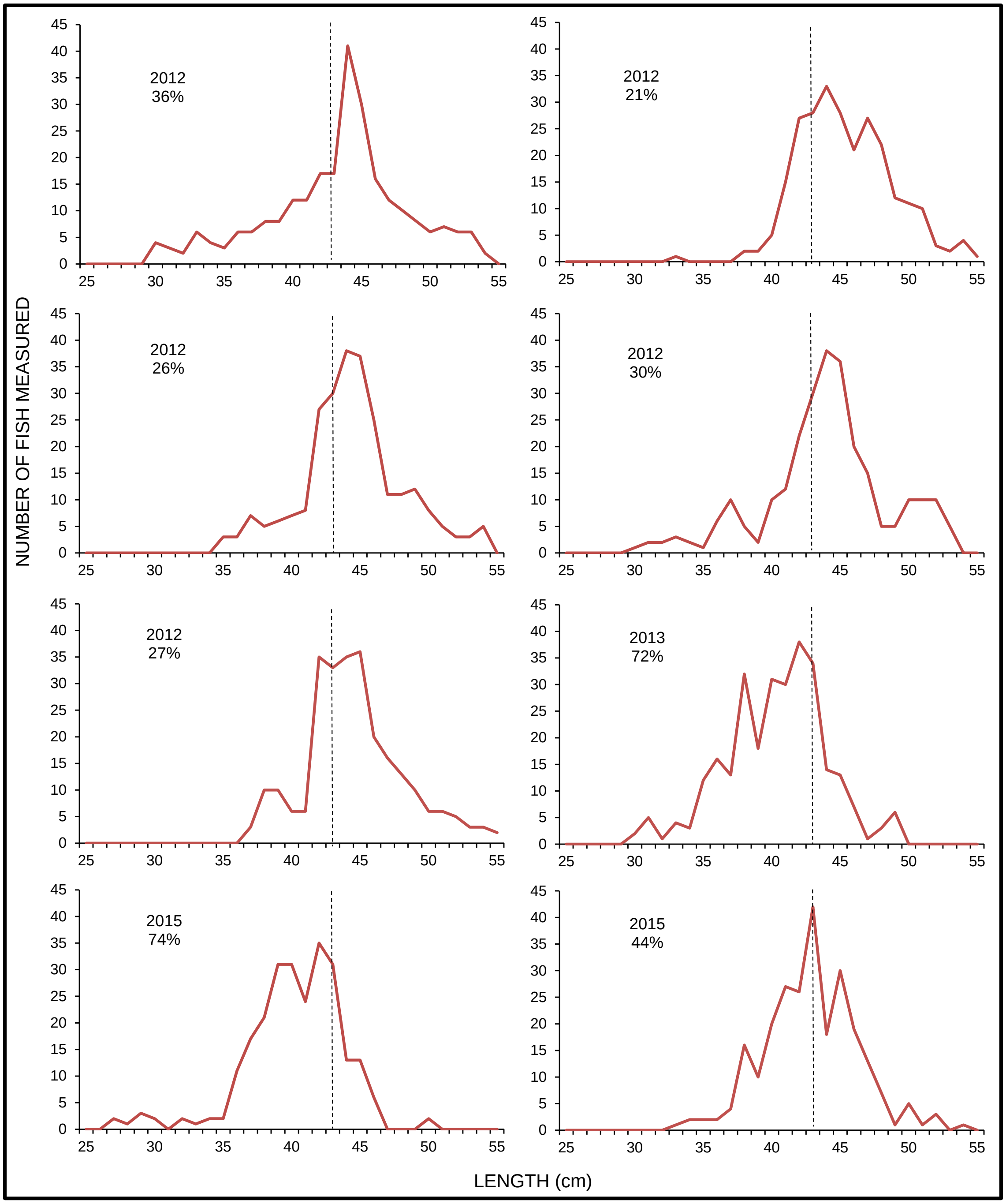

Figure 18. Length frequencies of Atlantic hagfish in sampled catches from the exploratory fisheries in the southern Gulf of St. Lawrence. Samples from 2012 and 2013 were taken on single trips by on-board observers. Samples from 2015 were obtained by dockside monitors from two landings. Dotted lines indicate the length corresponding to the preferred minimum size (80 g or 43 cm) of Atlantic hagfish for buyers for the leather industry. Each graph indicates the sample year and the percentage of the catch below 43 cm.

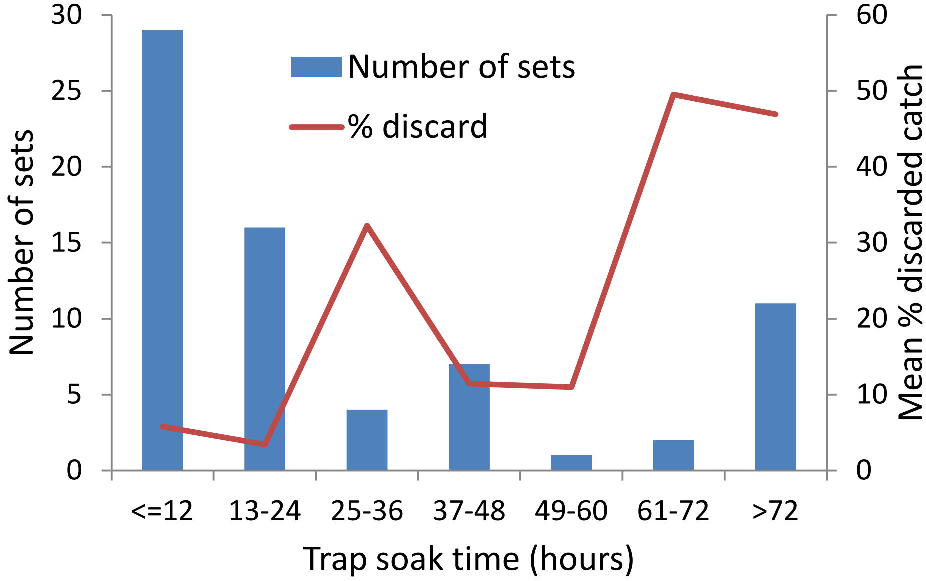

Figure 19. Relationship between the soak time of baited barrels in the Atlantic hagfish NAFO 4Tab fishery and the percentage by weight of discarded hagfish, based on logbook data, 2011 to 2015.