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Original Article

Impact of deep-sea fishery for Greenland halibut (*Reinhardtius hippoglossoides*) on non-commercial fish species off West Greenland

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Since the late 1980s, a deep-sea fishery for Greenland halibut (*Reinhardtius hippoglossoides*) has been developing gradually in West Greenland. Deep-sea fish species are generally long-lived and characterized by late age of maturity, low fecundity, and slow growth, features that probably cause low resilience following overexploitation. In order to evaluate whether populations of nine potential bycatch species are negatively affected by the commercial fishery for Greenland halibut, scientific data from bottom-trawl surveys conducted in the same area and period as the commercial fishery were analysed. During the period 1988–2011, population abundance and size composition changed as catch and effort in the Greenland halibut fishery increased. Two species showed a significant decrease in abundance, and four populations showed a significant reduction in mean weight of individuals ($p < 0.05$). Correlation analyses show that most of the observed trends in abundance are probably not related to increasing fishing effort for Greenland halibut. The analysis did, however, show that most of the observed decreases in mean weight were significantly correlated with fishing effort during the 24-year period.

Keywords: Abundance, bycatch species, deep-sea fisheries, Greenland halibut, mean fish size, West Greenland.

Introduction

Most analyses of the status of deep-sea fish stocks are focused on species targeted by commercial fisheries. The majority of exploited deep-sea stocks have been overfished or depleted to very low levels (Koslow *et al.*, 2000; ICES, 2012). There is only scarce information about potential bycatch species, but Bailey *et al.* (2009) reported that a number of deep-sea species southwest of Ireland had declined during 1977–2002 and ascribed this to increased fishing pressure. Casey and Meyers (1998) reported that the large bycatch species barndoor skate (*Raja laevis*) that lives on the shelf and upper slope in the Northwest Atlantic is close to extinction. Brander (1981) reported that the skate (*Raia batis*), common in the Irish Sea, has declined in abundance and is now very rare due to being taken as bycatch in fisheries targeting other species, and that a decline in abundance was also seen for other skates in the area. A study by Devine *et al.* (2006) concluded that five deep-sea fish species, common as bycatch in the deep-sea fishery for Greenland halibut (*Reinhardius hippoglossoides*) and redfish (*Sebastes spp.*) off eastern Canada, qualify as critically endangered, possibly as a consequence of commercial deep-sea fisheries. Four of the species, *Antimora rostrata* (blue hake), *Coryphaenoides rupestris* (roundnose grenadier), *Notacanthus chemnitzi* (spiny eel), and *Macrourus berglax* (roughhead grenadier), are also common in West Greenland waters, while the fifth species, *Bathyraja spinicauda* (spinytail skate), is less frequent.

A number of fishery management organizations around the world have implemented management and monitoring strategies to regulate deep-sea bottom fisheries in accordance with the precautionary and ecosystem approaches, but Large *et al.* (2013) show that the availability of reliable information on stock status and biology of most deep-sea fish stocks has lagged behind exploitation.

Effort and catches have overall increased substantially in the offshore commercial deep-sea fishery for Greenland halibut off West Greenland during the last 30 years. From 1981–1986, the annual officially reported catch in Northwest Atlantic Fisheries Organization (NAFO) Division 1CD, where the commercial fishery at West Greenland takes place, was below 500 t (NAFO, 2013). This amount excluded the catch by Greenland that was almost exclusively taken inshore (NAFO, 1990). In the late 1980s, offshore catches were ~ 2000 t, increasing gradually to 7200 t in 2011 (Jørgensen and Treble, 2012), with fishing effort increasing approximately fourfold. The fishery is almost exclusively conducted by trawlers fishing primarily between 800 and 1400 m depth, with an average of about 1050 m. The minimum mesh size in the trawl codend is 140 mm. There has been no analytical assessment of Greenland halibut; fishing mortality is not known, but is probably quite low (Jørgensen and Treble, 2012).

This paper evaluates whether the nine most abundant deep-sea fish species living near or at the bottom of the continental slope off West Greenland displayed declines in abundance or individual mean weight during the period 1988–2011 while catches of Greenland halibut increased substantially. All of these species are common in the fishing areas of trawlers targeting Greenland halibut and hence are potential bycatch in this commercial fishery (there is only very scarce information of bycatch in the logbooks). The nine species are characterized by late age of maturity, low fecundity, and slow growth, traits that are assumed to make them particularly vulnerable to being overfished (Koslow *et al.*, 2000).

Changes in abundance and mean weight of the nine species are analysed over a 24-year period, based on data from scientific bottom-trawl surveys conducted during 1988–2011 covering the same area as the commercial fishery for Greenland halibut. The survey data are used to assess whether changes in abundance or mean weight are correlated with changes in fishing effort in the Greenland halibut fishery. This hypothesis is tested through autocorrelation analyses of species abundance and mean weight trajectories, followed by cross-correlation analyses between effort development and the individual species trajectories.

Material and methods

Data were collected during 23 annual bottom-trawl surveys conducted between 30 April and 11 October 1988–2011 (no survey in 1996). The surveys, based on a stratified random design with at least two hauls per stratum (Doubleday, 1981), covered NAFO Div. 1C–D (62°30′N–66°15′N [0]) (Jørgensen, 1998a, 1998b). Only strata >800 m in depth were included in the analysis (Figure 1). The survey area was stratified by NAFO divisions and by depth as follows: 801–1000 m, 1001–1200 m, 1201–1400 m, and 1401–1500 m.

The surveys were conducted by two vessels—RV "Shinkai Maru" from 1988–1995 and RV "Paamiut" from 1997 to 2011—fishing with two different survey trawls. The trawls were, however, comparable, with net height ranging from 6.5–7.5 and 5–6.5 m, respectively, depending on depth, current, seabed, and trawling speed. Both trawls had 140-mm meshes, with a 30-mm liner in the codend and rockhopper ground gear. Further, towing time (30 min) and towing speed (2.8–3.5 knots) for both vessels were comparable. The two trawls had wingspreads of 37–45 and 20–25 m, respectively. For further information about trawl gear, see Jørgensen (1998a, 1998b). Abundance estimates were standardized to 1 km^2 swept area prior to further calculations, using the exact wingspread, towing speed, and towing time, and assuming a catchability coefficient for all species of 1.0. The total abundance and mean weight were estimated by species using stratum area as a weighing factor. All strata were covered in all years except for two small strata in 1993 and 1999, and three small strata had only one haul in 1988, 1992 and 2002.

The nine most abundant species in the bottom-trawl surveys that are not targeted in the commercial fishery for Greenland halibut and which were selected for further analysis were: *A. rostrata*, *C. rupestris*, *N. chemnitzi*, *M. berglax, Centrocyllium fabrici* (black dogfish), *Gaidropsaurus ensis* (threadfin rockling), *Synaphobranchus kaupi* (Kaup's arrowtooth eel), *Scopelosaurus lepidus* (blackfin waryfish), and *Coryphaenoides güntheri* (Günthers grenadier). Weight data were incomplete in 1988 for *C. güntheri, S. Lepidus*, and *G. ensis*; consequently, weight data for these species in that year were not included in the analysis.

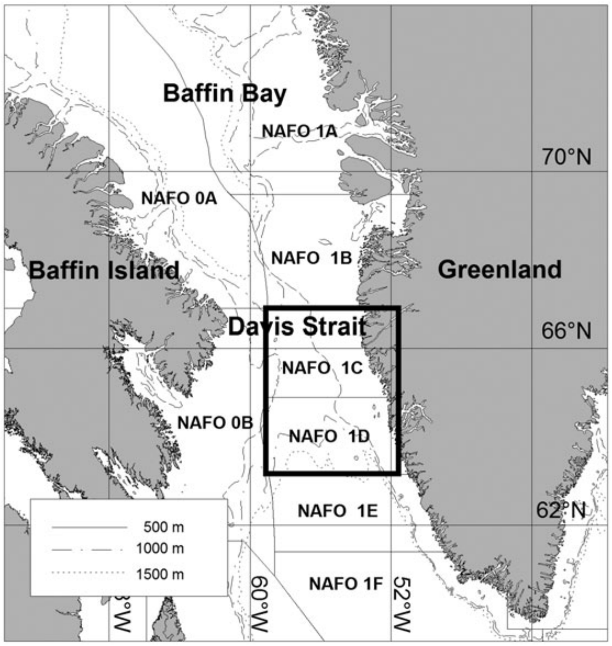

Figure 1. NAFO Subareas 0 and 1 showing divisions. The study area, Division 1CD is highlighted.

Yearly commercial fishing effort was estimated as $\sum$ fishing time × GT, where fishing time is in hours and GT (vessel gross tonnage as reported in the logbooks) is a proxy for fishing power (Reid *et al.*, 2011).

A linear least-squares regression was fitted to the survey time-series by species in order to evaluate changes in species abundance and individual mean weight in percentage between the starting and the ending year of the period (1988–2011). For each model, the significance of the estimated trend (i.e. the slope of the straight line) was tested for being different from a zero trend (from the F-statistics computed by the "lm" function of the R software (Venables and Ripley, 2002).

In order to test whether increased fishing effort in the Greenland halibut fishery has had a negative impact on the stock status of potential bycatch species, auto- and cross-correlations of the commercial and the survey time-series of effort, species abundance, and mean weights are analysed (computed by the "acf and ccf" function of the R software (Venables and Ripley, 2002). The cross-correlation analysis was carried out on previously detrended time-series to help detect short-term correlations, if any. (The detrending procedure consists of subtracting the predicted values of the linear model from the observed points of the time-series).

Results

Trends in fishing effort, catch, abundance and mean weight of Greenland halibut

Commercial catches of Greenland halibut increased significantly ($p < 0.001$) by 248% from 1988–2011 (Table 1, Figure 2). Catches

Table 1. Changes in effort, catch of Greenland halibut, and survey-based estimates of abundance and individual mean weight by species from 1988–2011.

	Abundance			**Mean weight**		
Species	**Significance level**	r^2	**Change in %**	**Significance level**	r^2	**Change in %**
Reinhardtius hippoglossoides	***	0.57	54.1	**	0.28	−13.8
Antimora rostrata	***	0.69	288.2	**	0.32	−29.5
Centrocyllium fabrici		0.05	−33.0	*	0.19	−26.4
Coryphaenoides güntheri		0.12	−43.3		0.09	29.9
Coryphaenoides rupestris	**	0.37	−100	***	0.64	−71.8
Notacanthus chemnitzi		0.05	15.2	**	0.37	−34.4
Gaidropsaurus ensis		0.04	−31.9	***	0.53	136.5
Macrourus berglax		0.11	48.9	+	0.14	−14.8
Scopelosaurus lepidus		0.09	48.4	+	0.14	−22.3
Synaphobranchus kaupi	**	0.36	−83.9	*	0.26	22.5

Significance code: ***$p = 0.001$, **$p = 0.01$, *$p = 0.05$, $^{+}p = 0.1$.

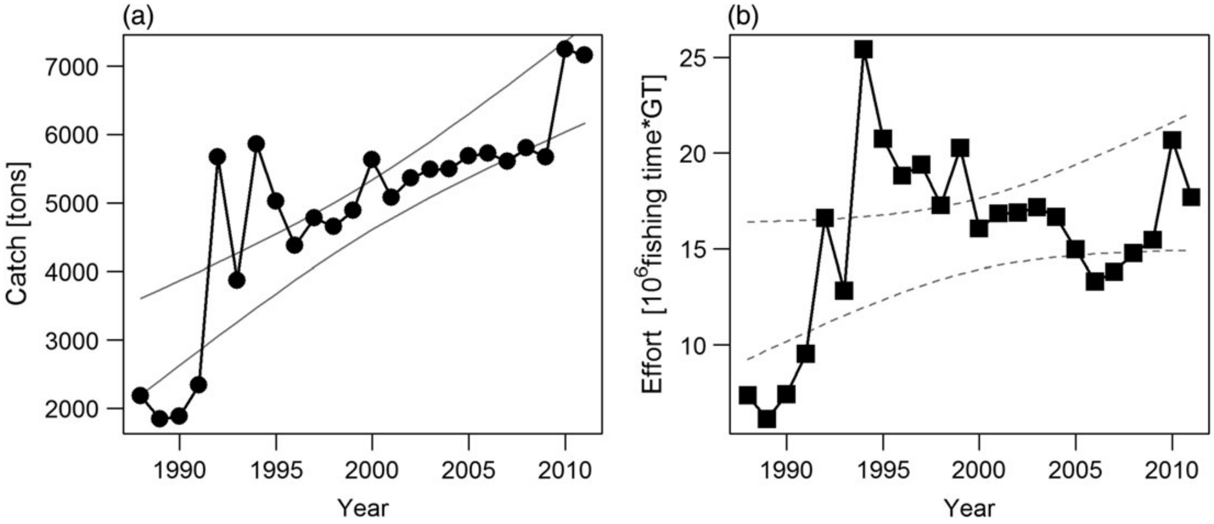

Figure 2. Catch of Greenland halibutin NAFO Divisions 1CD **(a)** and fishing effort **(b)** per year with 95% confidence interval of the linear regressions (solid lines: alpha < 0.05; dashed lines: $0.05 <$ alpha < 0.1).

increased between 1988 and 1995, were relatively stable between 1995 and 2009, and increased again in 2010 in response to an increase in total allowable catch (TAC). Fishing effort increased between 1988 and 1995 and then decreased gradually until 2009, probably due to an increase in stock size. The increase in effort between 2009 and 2010 coincided with the increase in TAC. The overall increasing trend in effort (Figure 2) is barely significant ($p = 0.068$). Despite the substantial increase in commercial catches of Greenland halibut, the survey-based abundance estimates underwent a statistically significant increase of 117% ($p < 0.001$) during the same period (Table 1, Figure 3). Effort probably did not increase at the same rate as catches because of the increase in stock size and a subsequent increase in catch per unit effort (cpue). Greenland halibut mean weight decreased significantly by 14% (Table 1).

Trends in abundance of bycatch species

Two of the bycatch species in the Greenland halibut fishery displayed significantly decreasing trends in abundance ($p < 0.01$), while one species increased in abundance during the period. Abundance of *C. rupestris* decreased by ~ 100%, and that of *S. kaupi* by about 84%. In contrast, abundance of *A. rostrata* increased by ca 288% from 1988–2011 (Table 1, Figure 4). For the remaining six species, the survey time-series indicated decreasing trends for three (*C. fabrici*, *C. güntheri* and *G. ensis*) and increasing trends for the other three (*N. chemnitzi*, *M. berglax* and *S. lepidus*), but these trends were not statistically significant (Table 1, Figure 4).

Trends in mean weight of bycatch species

During the period, mean weight decreased significantly ($p < 0.05$) for four of the nine bycatch species (*A. rostrata*, −30%; *C. fabrici*, –26%; *C. rupestris*, −72%; and *N. chemnitzi*, −34%), but increased significantly for two species (*G. ensis*, 137%; *S. kaupi*, 23%) (Table 1, Figure 5). The survey time-series indicates decreasing mean weight of *M. berglax* and *S. lepidus* and increasing mean weight of *C. güntheri*, but these trends were not statistically significant.

Auto- and cross-correlation

The commercial effort time-series (1988–2011) was relatively well-contrasted across the time-series, with low effort before 1991 and high effort after 1995 (Figure 2), and there is a significant

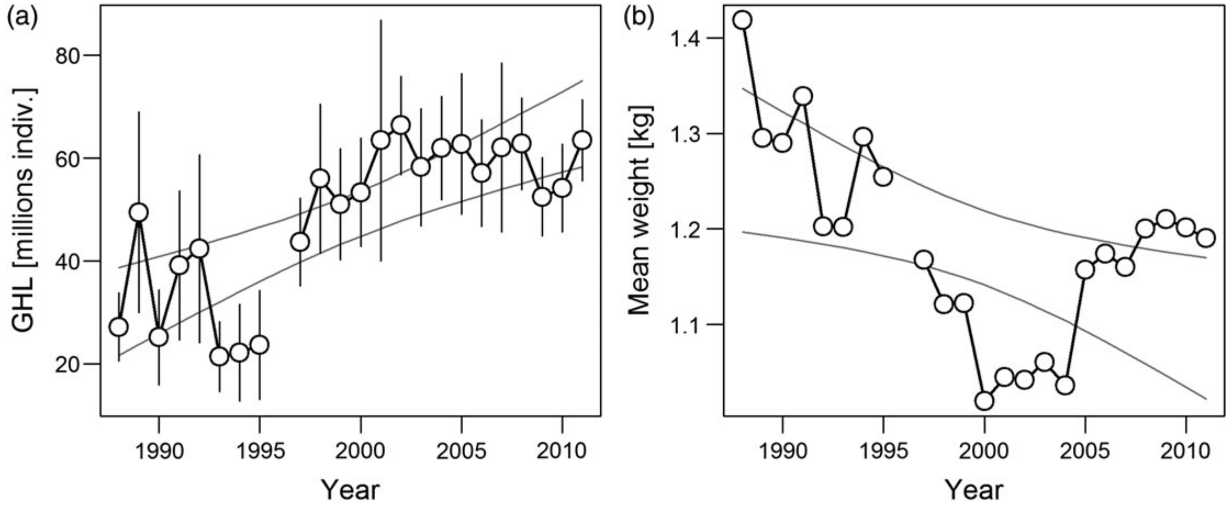

Figure 3. Survey population abundance **(a)** and individual mean weight **(b)** of Greenland halibut with 95% confidence interval of the linear regressions (solid line: alpha < 0.05).

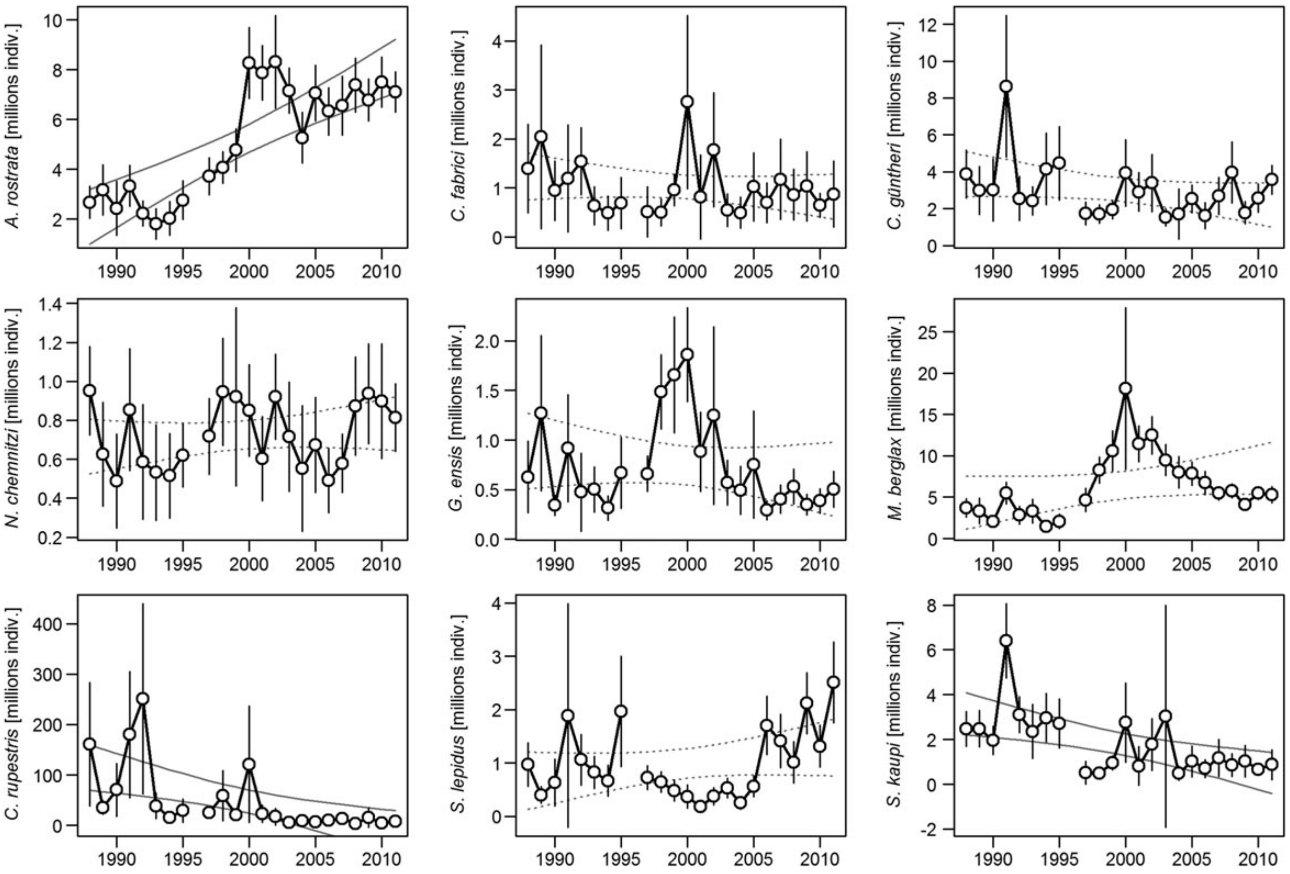

Figure 4. Abundance by species and year in surveys. Each abundance is given with 95% confidence interval.

autocorrelation on 1 year (outside the range $-0.4 < r < 0.4$, corresponding to 95% confidence limits for the correlogram (Venables and Ripley, 2002), indicating that there were only small changes in effort between consecutive years (Figure 6).

There was no significant autocorrelation pattern in abundance estimates for *C. fabrici*, *C. güntheri, N. chemnitzi, C. rupestris*, *S. lepidus* or *S. kaupi*, while autocorrelation patterns were found for *A. rostrata, R. hippoglossoides, M. berglax* and *G. ensis* (Figure 6).

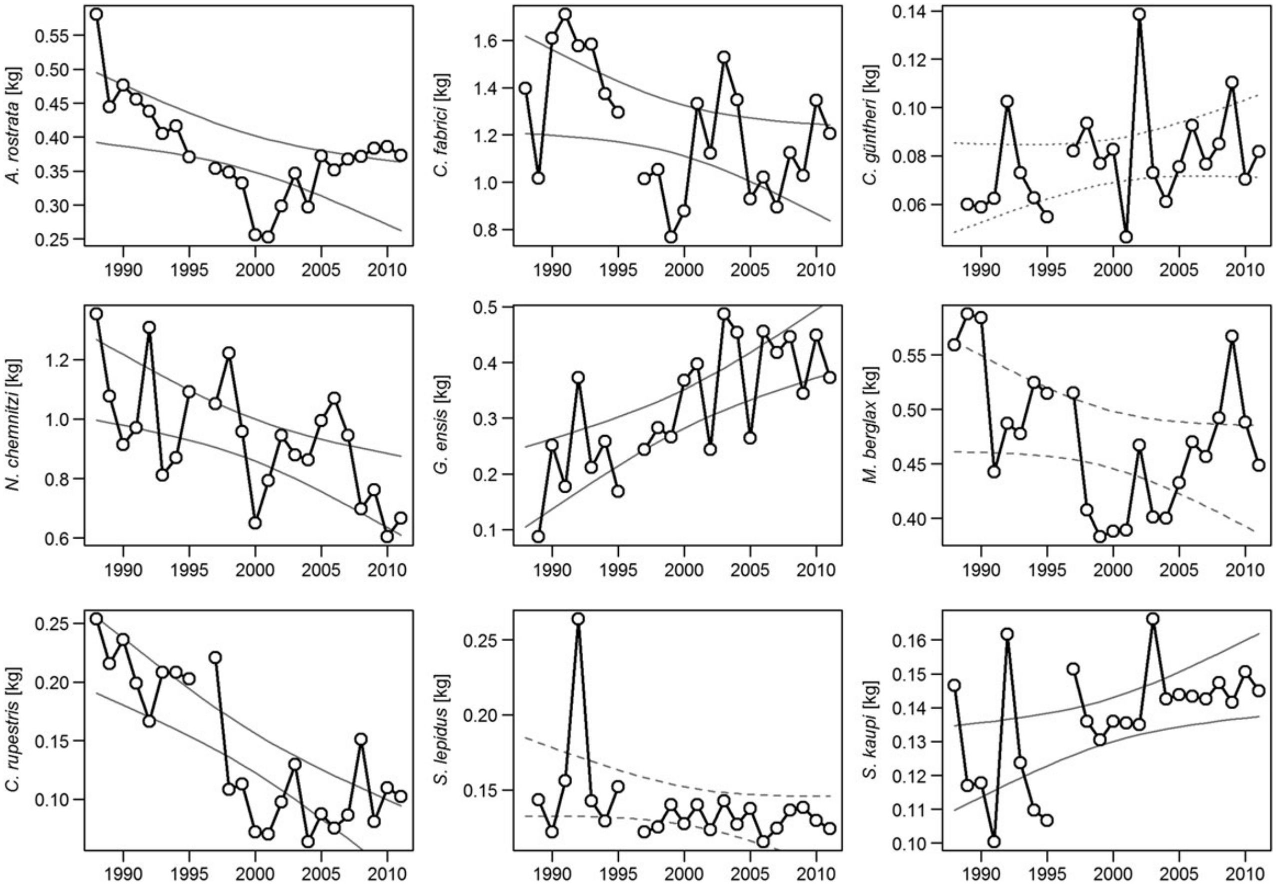

Figure 5. Changes in individual mean weight by species and year. The 95% confidence interval of the linear regression is also given (solid line: alpha < 0.05; dashed line: $0.05 <$ alpha < 0.1; otherwise dotted line).

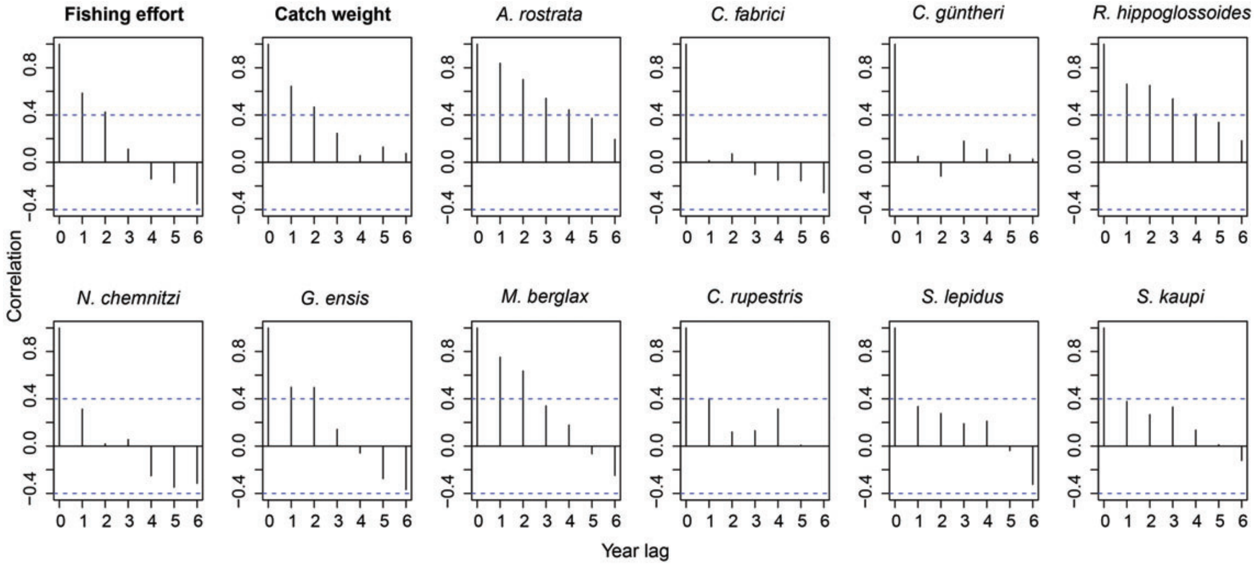

Figure 6. Autocorrelation analyses of the overall fishing effort, catch in tonnes, and abundance time-series by species.

In terms of individual mean weight, there was no significant autocorrelation pattern for *C. güntheri*, *N. chemnitzi*, *S. lepidus* or *S. kaupi*, while the mean weight for *A. rostrata*, *R. hippoglossoides*, *M. berglax*, *G. ensis*, *C. rupestris* and *C. fabrici* showed a lag pattern (Figure 7).

The analysis on the detrended time-series (Figure 8) of cross-correlations reveals that the abundance of *S. lepidus* and *S. kaupi* was negatively correlated with high effort, with a lag of 2–6 y. On the contrary, the abundance of *G. ensis*, *M. berglax* and

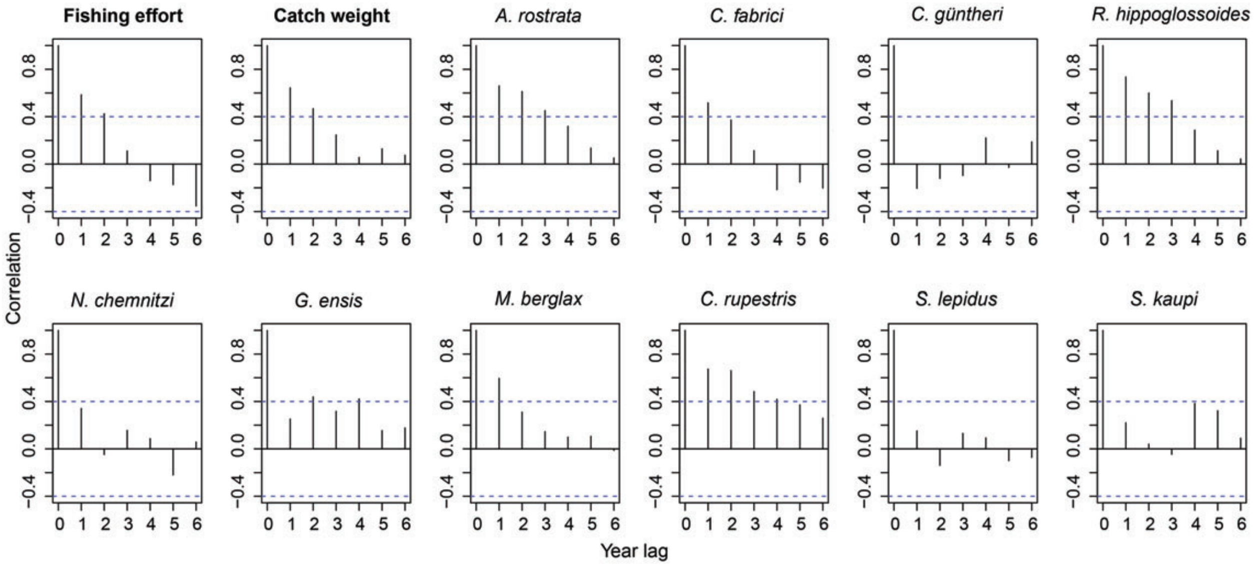

Figure 7. Autocorrelation analyses of the overall fishing effort, catch in tonnes for mean weight time-series by species.

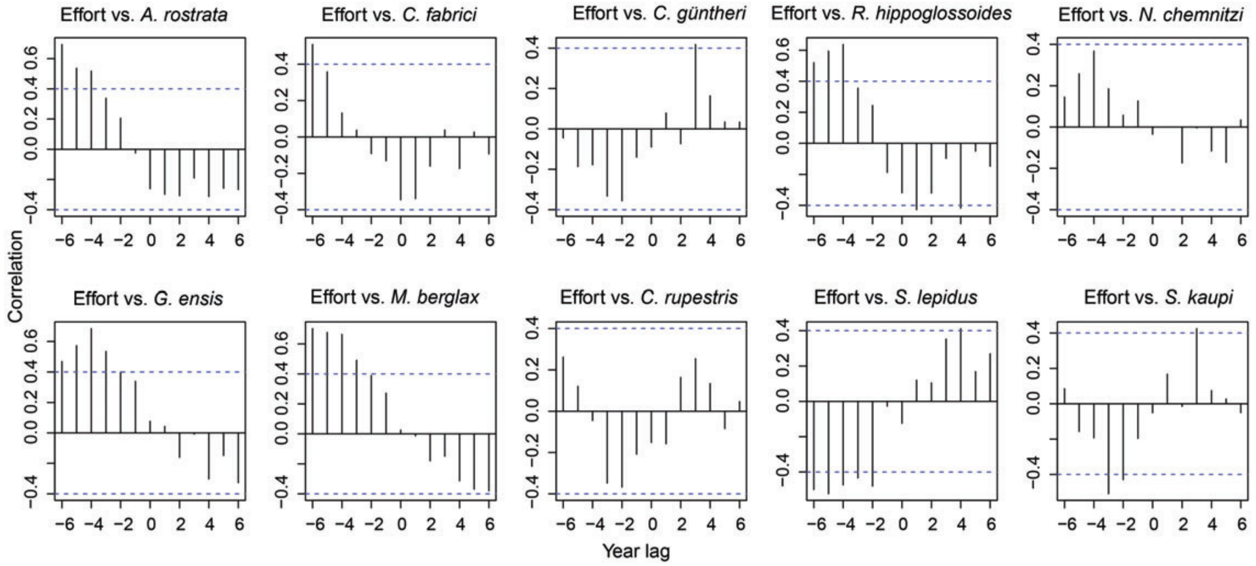

Figure 8. Cross-correlation of commercial effort and abundance of the nine potential bycatch species.

R. hippoglossoides was positively correlated with high effort, with a time lag of ca 3–6 y.

A significant negative cross-correlation between effort and individual mean weight was observed for *A. rostrata*, *C. fabrici*, *R. hippoglossoides*, *M. berglax*, *C. rupestris* and *S. lepidus*, with a high level of effort (Figure 9).

Discussion

A large number of deep-sea fish species are long-lived and characterized by late age of maturity, low fecundity and slow growth, which also applies to the nine species included in the present analyses (http://www.fishbase.org). These features probably result in low resilience to overexploitation (Koslow *et al.*, 2000), and the deep-sea fishery for Greenland halibut in West Greenland waters could potentially have a severe negative effect on bycatch species, as observed in deep-sea fisheries elsewhere in the Northwest Atlantic (Devine *et al.*, 2006) and Northeast Atlantic (Bailey *et al.*, 2009).

While the fishery for Greenland halibut increased substantially during the period 1988–2011, the nine studied stocks developed in various ways at the same time. Two of the species [*C. rupestris* (100 %) and *S. kaupi* (84%)] showed a statistically significant decrease in abundance, and three other species were also reduced in numbers, however, this was not statistically significant (*C. fabric*, −22%; *C. güntheri*, −43%; and *G. ensis*, −33%). The decreases could have been caused by bycatch in the fishery for Greenland halibut, but also by decreased recruitment, migration out of the area, or increased predation by *R. hippoglossoides*, the abundance of which increased by 117% during the period studied.

Statistically significant autocorrelation is typical of stable abundance trajectories arising from situations of stable recruitment, low

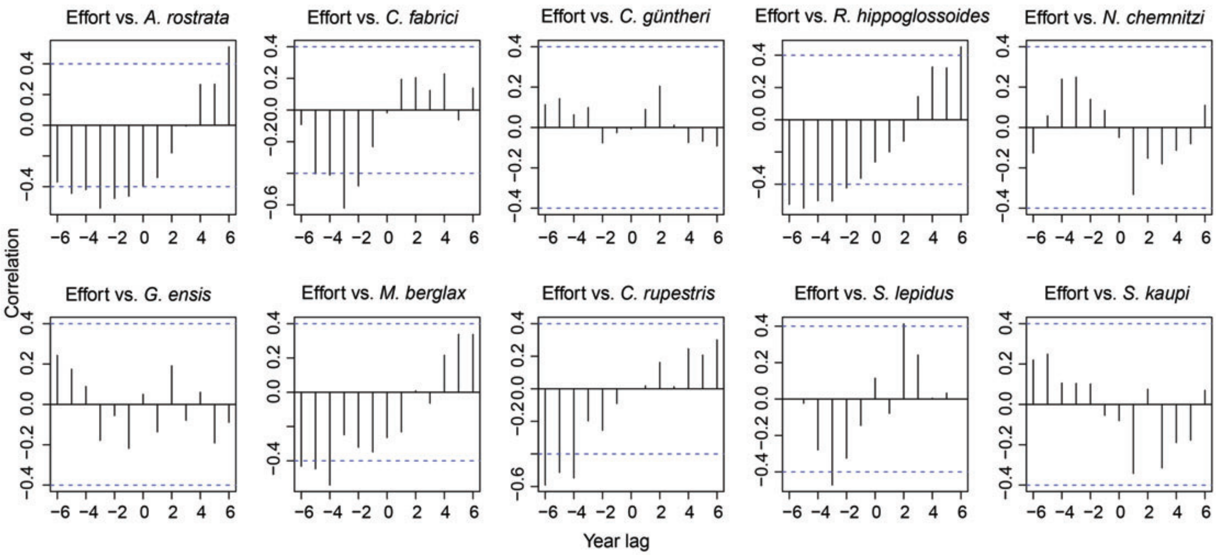

Figure 9. Cross-correlation of commercial effort and mean weight of the nine potential bycatch species.

migration rate, or low variation in harvesting pressure. The autocorrelation patterns for abundance for *C. fabrici*, *C. güntheri*, *N. chemnitzi*, *C. rupestris*, *S. lepidus* and *S. kaupi* and for mean weight for the same species except for *C. rupestris* and *C. fabrici* are statistically insignificant (95% level), indicating that these stocks are influenced by external factors such as change in recruitment, emigration, immigration, change in natural mortality, or increasing fishing effort (Figures 6 and 7).

A significant cross-correlation between the time-series of commercial fishing effort and abundance and mean weight would, however, suggest that fishing pressure could be a key factor explaining the observed trends in terms of numbers and individual mean weight. The cross-correlation analysis shows that the abundance of *S. lepidus* and *S. kaupi* is negatively correlated with high effort, with a lag of 2–6 year, indicating that high and/or accumulated effort has an impact on the abundance of the two species.

Changes in individual mean weight over time can give some indication about the underlying stock dynamics caused by fishing pressure (Koslow *et al.*, 2000). A significant negative cross-correlation between effort and individual mean weight was observed for six species (*A. rostrata*, *C. fabrici*, *R. hippoglossoides*, *M. berglax*, *C. rupestris* and *S. lepidus*) with high level of effort, indicating that the fishery has removed the larger individuals of the populations (Figure 9).

The commercial fishery for Greenland halibut thus seems to have a relatively small influence on the abundance of the nine most common potential bycatch species, while the mean weight of a larger number of species seems to be affected by the fishery. The fishery for Greenland halibut at West Greenland is conducted in a rather small area compared with the much wider distribution area of all nine deep-sea species included in the analysis (Whitehead *et al.*, 1986), and most of the species analysed are at the rim of their distribution area (Jørgensen *et al.*, 2011), suggesting that stock dynamic processes outside the fishing area might influence the dynamics of these stocks within the fishing area. *M. berglax* is the only species known to spawn regularly in the study area (Jensen, 1948). Jørgensen (1996) reported that there was no sign of spawning by *C. rupestris* or *C. güntheri* in the study area; most of the recruitment is presumably from elsewhere in the North Atlantic, brought to the area by the relatively warm West Greenland current that is a branch of the Gulf Stream and the Irminger Current (Buch, 2000).

Devine *et al*. (2006) observed dramatic declines in abundance between 93 and 99% for *C. rupestris, M. berglax, A. rostrata* and *N. chemnitzi* off eastern Canada in an area with fisheries for Greenland halibut and redfish, and Bailey *et al.* (2009) documented a significant decrease in stock size for *C. rupestris* in the Mid-Atlantic. Apart from *C. rupestris,* which also declined significantly in West Greenland, the other three species increased in abundance (not statistically significant for *M. berglax*) in West Greenland from 1988–2011, suggesting that the abundance decline observed off eastern Canada is a local phenomenon.

The steep decline in abundance of *C. rupestris* in West Greenland is probably not caused by the fishery, as also indicated by the insignificant cross-correlation with effort for this species. In 1986, abundance was estimated at ~ 445 million fish, of which the vast majority was found in West Greenland waters (Atkinson and Bowering, 1987). Since then, abundance exhibited a steep decline and was estimated at ~ 25 million fish in 1990. In the same period, the commercial fishery for Greenland halibut was very limited ($<$2500 t annually, Jørgensen and Treble, 2012), and the reported catches of *C. rupestris* were $<$300 t annually (NAFO, 2013). Furthermore, it is not likely that the generally small *C. rupestris* could have been taken in such quantities as bycatch in a fishery with a minimum mesh size of 140 mm (Jørgensen, 1998a). The decline must, therefore, have been caused mainly by natural mortality or migration out of the area.

The analyses and results in this study could potentially have been biased due to (i) the use of two different vessels with different trawl gear in the scientific bottom-trawl surveys, and (ii) the data limitations in the calculation of the effort time-series.

Regarding (i), there has not been any comparative trawling in order to evaluate possible differences in catchability of the two trawls. Both trawls did, however, have the same mesh size and the same type of ground gear, and all catches were standardized to catch km^{-2} in order to compensate for differences in wingspread and variation in trawled distance between hauls, but the changes in abundance estimates from year to year were often larger within trawl series than between the two series, indicating that catchability of the two trawls was comparable (Figure 4). It has not been possible to compensate for the difference in trawl height between the two trawls. If the difference in trawl height between the first and second half of the survey time-series had an effect on catchability of the trawl series, it probably had an effect on the catchability of the bathypelagic species. Such an effect would tend to amplify any declining trends in population abundance.

Regarding (ii), vessel engine power would probably have been a better proxy for fishing power than gross tonnage (Eigaard and Munch-Petersen, 2011; Eigaard *et al.*, 2011a), but because engine power data are not routinely recorded for all vessels in the commercial Greenland halibut fleet, gross tonnage was used instead for calculating effective effort (Reid *et al.*, 2011). The resulting effort time-series of our correlation analyses could potentially be biased from this choice, and furthermore the observed increase is probably underestimated due to the inability (lack of data) to incorporate technological creep in the calculations of effective effort (Marchal *et al.*, 2007; Eigaard *et al.*, 2011b). Corrections of any underestimation of effective effort would, however, most likely not change the directionality of our results.

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