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EXECUTIVE SUMMARY

Based on summer trawls surveys along the West Greenland coast and shelf, the spatio-temporal variation in the demersal fish community was quantified between 1993 and 2016. A substantial change was observed with 4 to 10-fold increase in total biomass, increase in the average size of specimens and an increase in the average trophic level in net hauls. Findings suggest a substantial quantitative and qualitative change in the importance of demersal fish for the coastal food web with likely cascading effect to trophic levels below and above. Based on near-bottom temperature measured on the trawl gear we identify slight warming trends in the northern region and in the two deepest depth strata (200-600 m). When compared to decadal variability based on CTD data from available data bases we find that the recent warming trend is not outside the range of a previous "warm period" in the 1930s underlining the importance of identifying decadal variability in climate. Decreasing fish mortality from shrimp by-catch contributed to improved mitigation practice combined with decreased fishing effort is identified as a major driving factor. However, it coincides with atmospheric warming and consequently reduction in sea ice concentration and increased summer run-off from the Greenland Ice Sheet, which improve light and nutrient for primary production. Thus, it is an important example of how recovery from over-exploitation may be shaped by climate change.

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1. Foreword

This report describes progress on analyzing spatio-temporal variation is demersal fish density from the fish surveys conducted by the Greenland Institute of Natural Resources since 1989. It has been a considerable challenge to quality control and standardize the data set. To this end, the early part of the time series has been omitted, a large fraction of net tows from depths below 600 and using a specific trawl type has also been omitted from further analysis. Finally, due to variable taxonomic expertise between years, we have chosen to focus on the dominant species (based on biomass). We present a descriptive analysis of changes, and find a substantial increase in biomass and average individual size combined with changes in composition of dominant species and average trophic level. Since ocean temperature is an essential component driving distribution of species but also indicate shift in water mass properties, we searched available data based on ocean temperature. A preliminary analysis with observation from 1932 is presented. The assimilation of all available temperature data in a spatio-statistical model is work in progress together with partners in WP5.
The final version of this work will be submitted in M54. The planned work includes presentation of this report for fishery biologists and stakeholders in Greenland, November 2020. After input from Greenland, a multivariate statistical analysis will be conducted with statisticians from AU which will include analysis of shift in depth distribution of individual species to compensate for changes in temperature before the final report is submitted.

2. Introduction

Fish populations are among the best studied marine populations in the Arctic and can provide time series data that allow analysis of decadal changes and identification of potential drivers of change. The impact of climate change and increasing ocean temperature on distributional changes in fish has been addressed by numerous studies. Increasing ocean temperature have been linked to range expansion of boreal species in both Arctic water (Fossheim et al. 2015) and elsewhere (Burrows et al. 2019), which implications for food web structure and ecosystem function (Grebmeier et al. 2006; Kortsch et al. 2017). However, as commercial fisheries are important in several Arctic regions, the effect fisheries on commercial species and through by-catch needs to be considered and included when trying to tease out the multiple drivers of changes in fish assemblages. Finally, it has been demonstrated that other factors can be more important than temperature for shaping fish assemblages and their distribution (Li et al. 2019). The fisheries in Greenland is the dominant industry and responsible for more than 90% of the national export. Historically, cod has been the key species targeted by fisheries and Atlantic and Greenland cod has been commercially fished since the 17th century. Warming ocean temperatures and successively-high year classes of cod in the 1930s led to a rapid expansion of the Greenlandic fishery (Jensen 1949). After a period of reduced fishing activity in the 1940s, the decades of the 1950s and 1960s ushered in a wave of increased catches for Atlantic cod with peak catches of more than 400.000 tons in the 1960s (ICES 2019). Then followed a series of repeated crashes of the cod stocks. The decline of cod in the late 1960s and early 1970s uncovered the dominance of local, inshore cod, and unexpectedly, of the migrating cod stocks of Icelandic origin. The collapse of the offshore cod stock of the early 1990s marked the major overall crash in terms of stock (Hovgård and Wieland 2008). The industry switched to northern shrimp fisheries, and inshore and offshore fisheries grew in the 1990s, particularly of Greenland halibut. In a study of demersal fish biomass and species richness (Rätz 1999) concluded that despite a warming trend in bottom waters, the reduction in fish biomass from 1986 to 1998 in West Greenland fish stocks was related to depleted spawning stocks and by-catches from the shrimp fisheries.

The aim of this study is to quantify trends in demersal fish populations along the West Greenland coast and shelf. Whereas single commercial species are treated in detail by the Fisheries Management in Greenland, our purpose is to quantify trends from an ecosystem perspective, identify potential drivers of change and discuss consequences for the Baffin Bay food web.

3. Method

Study area

The SW Greenland coast is dominated by large glacial fjords, that receive increasing amounts of glacial ice and meltwater from the Greenland Ice Sheet (Bamber et al. 2012). The shelf is relatively narrow (< 100 km in the south, but extends gradually towards north. Interspersed on the shelf are several shallow banks, with depths less than 100 m with narrow and deeper troughs in between. Sea ice cover the northern part of the Baffin Bay in winter with the ice coverage extending to the Disko Bay region at 69°N (Onarheim et al. 2020). The area is dominated by the northward flowing West Greenland current that forms at the southern tip of Greenland where two water masses meet; warm and salty Irminger Water subducts below the less saline and cold polar water from the East Greenland Current (Myers et al. 2009). As these two components of the West Greenland current flow north they are modified by exchange with the numerous fjord systems (Mortensen et al. 2011). Relative changes in the magnitude and distribution of warm Irminger water and cold polar water results in considerable variability in ocean temperature on the shelf (Buch et al. 2004).

Trawl surveys

Data from the summer bottom trawl surveys conducted by the Greenland Institute of Natural Resources were analyzed. The survey is based on a stratified semi-systematic design primarily to estimate the northern shrimp stock biomass. The trawl type was changed in 2005 when the "Skjervoy 3000" trawl was replaced by a "Cosmos 2000". Both trawls where used in 2004 and 2005 for calibration purposes with focus on shrimp size classes (Rosing & Wieland 2005). Here, we assume that catchability of the two nets are similar, but include trawl type as a factor in the statistical analysis. From each net haul three metrics are measured: a) the concentration of fish species at each station (individuals/km^2), b) the total biomass of each species (kg/km^2), c) the average individual weight per species (kg) calculated as total biomass/number of individuals. We assigned a trophic level for each species based on information in FishBase.org and Nielsen and Andersen (2001), and this information was used to calculate the average trophic level in each net tow, by weighing the contribution from each species based on its biomass in each net haul. Before analysis, survey data was quality controlled. Since the capacity for identification of rare species varied between years, we only include the 33 most common species, based on biomass. For some taxa such as red fish identification to species level can be problematic, and species where pooled at genera level. To have consistent depth and latitude range data was constrained to the period from 1993 to 2016 and at depths less than 600 m. We included hauls between 59 and 73 ºN. Only valid hauls with a tow duration of at least 0.1 km were included. From 1995 data included near bottom temperature for each net tow.

CODE	Scientific name	Common name
WIT	*Glyptocephalus cynoglossus*	Witch flounder
WHB	*Micromesistius poutassou*	Blue whiting
CFB	*Coryphaenoides brevibarbis*	Shortbeard grenadier
RNG	*Coryphaenoides rupestris*	Roundnose grenadier
SER	*Serrivomer beani*	Stout sawpalate
ARS	*Argentina silus*	Greater argentine
CAD	*Anarhichas denticulatus*	Northern wolffish
SYN	*Synapobranchus kaupi*	Kaup's arrowtooth eel
HAD	*Melanogrammus aeglefinus*	Haddock
MYX	*Myxine glutinosa*	Atlantic hagfish
ARZ	*Arctozenius rissoi*	Spotted barracudina
XONA	*Gaidropsarus spp.*	
CHA	*Chauliodus sloani*	Sloane's viperfish
COD	*Gadus morhua*	Atlantic cod
STO	*Stomias boa*	Boa dragonfish
CAA	*Anarhichas lupus*	Atlantic wolffish
PLA	*Hippoglossoides platessoides*	American plaice
GHL	*Reinhardtius hippoglossoides*	Greenland halibut
CAS	*Anarhichas minor*	Spotted wolffish
CAP	*Mallotus villosus*	Capelin
LUM	*Cyclopterus lumpus*	Lumpsucker
RRD	*Raja radiata*	Starry skate
XART	*Artediellus spp.*	
ELZ	*Lycodes sp.*	Eelpout
POC	*Boreogadus saida*	Polar cod
LEM	*Leptoclinus maculatus*	Daubed shanny
ASP	*Aspidophoroides monopterygius*	Alligatorfish
XEUD	*Agonidae*	
CAR	*Careproctus reinhardti*	Sea tadpole
EUM	*Eumicrotremus spinosus*	Atlantic spiny lumpsucker
GRC	*Gadus ogac*	Greenland cod
XMSC	*Myoxocephalus sp.*	Sculpin
EPR	*Eumesogrammus praecisus*	Fourline snakebenny

Table 1. Abbreviation for the 33 dominant species/taxa included in the survey

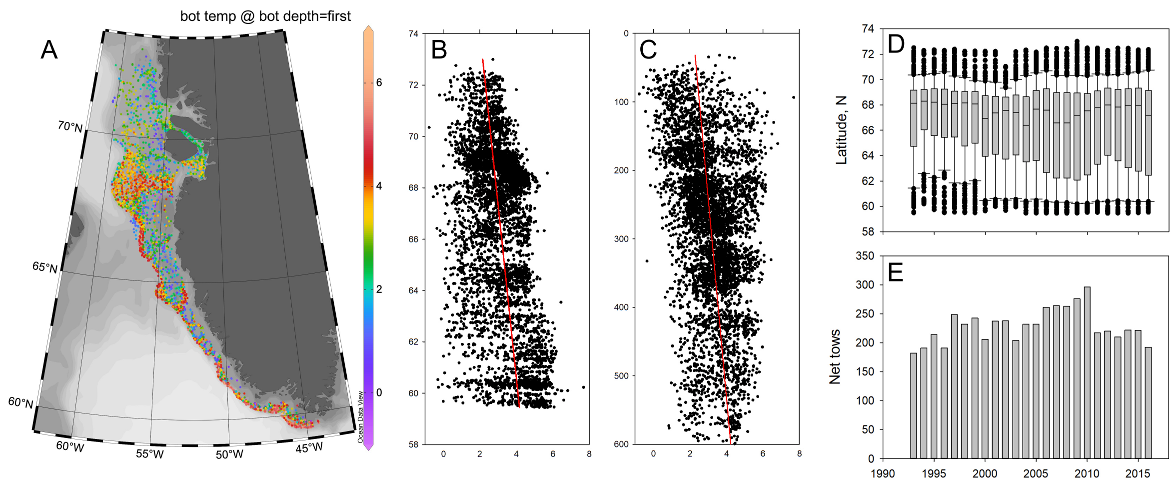


Figure 1. A Distribution of the bottom trawls along the West Greenland shelf used in this study and the near bottom temperature measured for each trawl B. Distribution of measured near bottom temperature across the latitudinal range. C. Near bottom temperature as a function of bottom depth. D. latitudinal distribution of net hauls in the study period 1993-2016. E. Number of net hauls for each year.

4. Results

The distribution of the all trawls tows and the near bottom temperature along the SW Greenland shelf is shown in Fig 1A. Although a temperature varied considerably within a given latitude the average bottom decrease from north to south and the range in temperatures are lower at higher latitudes (Fig 1B). Due to the two water masses there was a tendency towards higher temperature at intermediate depths of 100-250 m. The latitudinal distribution of trawls, shows near similar range and median across years (Fig 1D) and although the sampling effort changes between year, no trend during the time period is seen (Fig 1E). To quantify trends in temperature we analyzed data in 1° latitudinal bands and in three depth strata (0-200, 200-400 and 400-600 m depth). The average temperature show that lowest temperatures was found in the upper 200 m and that highest temperature was consistently found in the deepest depth stratum (Fig 2A). We calculated the linear slope for each grid cell, and although most cells did not display a statistically significant trend it show that changes are not uniform. In general, a cooling was found in the surface layer, and the deeper strata showing a difference with a general warming trends found north of 66 and a cooling trends, south of 66 mostly in the 200-400 m strata (Fig 2b). Based on this we have analyzed the biological response separately for the regions north/south of 66ºN.

To put our temperature data and study period in a long-term perspective we analyzed summer data from a repeated CTD transect at 64 ºN. Water column data representative for our three depth strata show a general increasing trend during 1993-2016, but compared to the full time series with data points extending back to the 1930s it can be seen that seen that despite the recent warming, temperatures are not outside the range measured before.

A

Latitude	0-200	200-400	400-600
59	4.0	4.1	5.2
60	2.7	3.9	4.8
61	2.8	4.3	5.2
62	1.4	3.5	4.8
63	1.5	2.9	4.2
64	1.6	2.9	4.1
65	1.6	2.2	4.2
66	2.0	2.3	3.6
67	2.4	2.8	3.6
68	1.3	2.8	3.6
69	1.0	2.4	2.9
70	0.4	2.4	2.6
71		1.9	2.7
72		2.0	2.6

B

Latitude	0-200	200-400	400-600
59		0.00	-0.05
60	-0.10	-0.04	-0.01
61	-0.06	-0.05	0.00
62	-0.07	-0.06	0.00
63	-0.02	-0.06	0.00
64	-0.04	0.00	0.02
65	0.06	0.03	-0.01
66	-0.08	0.02	0.02
67	-0.15	0.03	0.04
68	-0.15	0.05	0.04
69	-0.07	0.03	0.05
70	-0.11	0.04	0.04
71		0.04	0.03
72		0.06	0.04

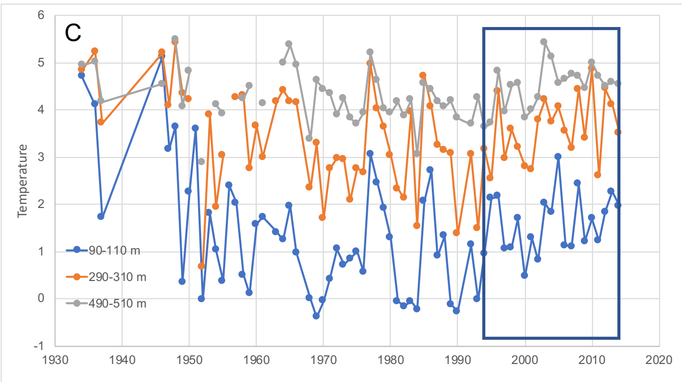


Figure 2. A. Average near-bottom temperature during summer for 1993-2016 in 1° sections for latitudes between 59 and 73°N and for three depth strata; 0-200 m, 200-400 m and 400-600 m. B Linear trends for temperature in the same grids. C long term variability in ocean temperature on the SW Greenland shelf at approximately 64N. Measurements from a repeated CTD transect and obtained from the ICES data base and temperature calculated for three depth strata corresponding to bottom depth strata. The black box marks the study period for trawls surveys used in this study.

To characterize the selected species found in net hauls, we calculated the average temperature and latitude for the trawls where each species where found (Fig. 3). The preferred temperature for each species ranged from below 2 to above 4.5ºC. Not surprising, the species with high average temperature, also had a lower latitudinal distribution. We split the species in two groups; a group with a warm/southern affinity roughly corresponding to average temperatures >3ºC and latitude <66ºN and a cold/northern group with a distribution at temperatures <3ºC and north of 66ºN.

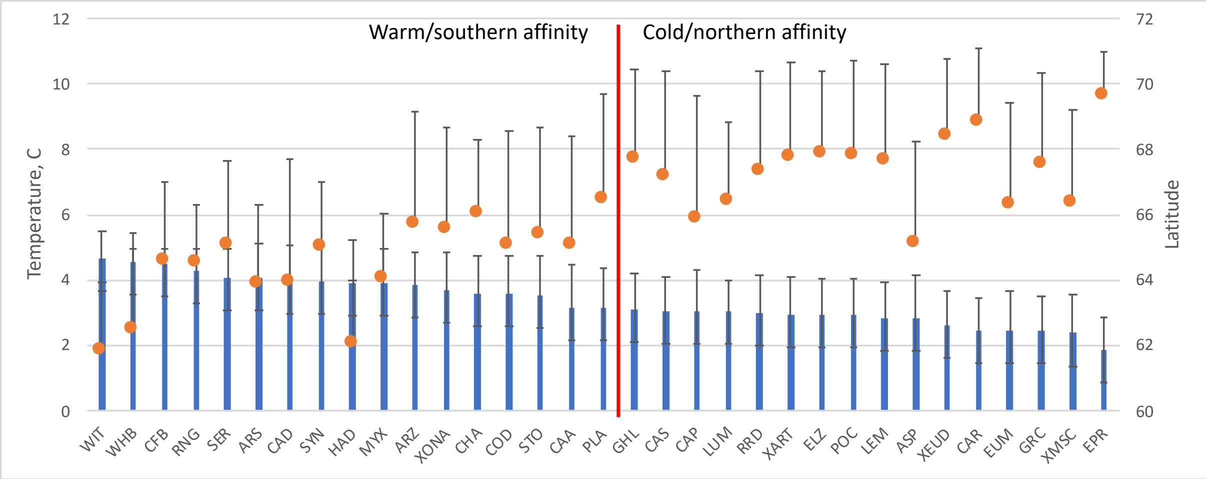


Figure 3. Average temperature (bars) and latitude (circles) (± SD) of net hauls where each of the 33 taxa where observed. The species where split into two groups; one with a preference for temperatures > 3ºC and latitudes < 66ºN and one with preference for colder temperature and higher latitudes (Temperature < 3ºC and latitude > 66ºN. See table 1 for full species names

To characterize the fish community change over time, we analyzed changes in total biomass, average individual size, average number of species per trawl haul and the average trophic level of species caught in each trawl. The total biomass was relatively constant from 1993 to 2003 with average biomass of 200-600 kg km^{-2} made up almost exclusively by species from the cold/north affinity group (Fig 4B). In 2005, total biomass increased, driven by the increase in biomass of warm/south species, which now contribute near 50%. Cold/northern species also contributed to the increase in biomass. In 2013, 2014, and 2015, average biomasses exceed 2000 kg km^{-2}, with 2015 peaking at 4000 kg km^{-2}. It should be noted that the large average biomass in these years are influenced by a smaller number of net hauls with very high biomasses, a problem often found in fishery biology due to the schooling behavior of some species. In 2016, average biomass decreased to 1400 kg km^{-2} but still with a near 50% contribution from the warm/south group. The average number of taxa in each net haul, remained pretty constant over time at 6-8 species, but with an slight increasing trend for south/warm species from on average 1.5 to 2.5 species per net haul, while the north/cold group from 5-6 species per haul to roughly 4-5 species at the end of the sampling period (Fig. 4A).

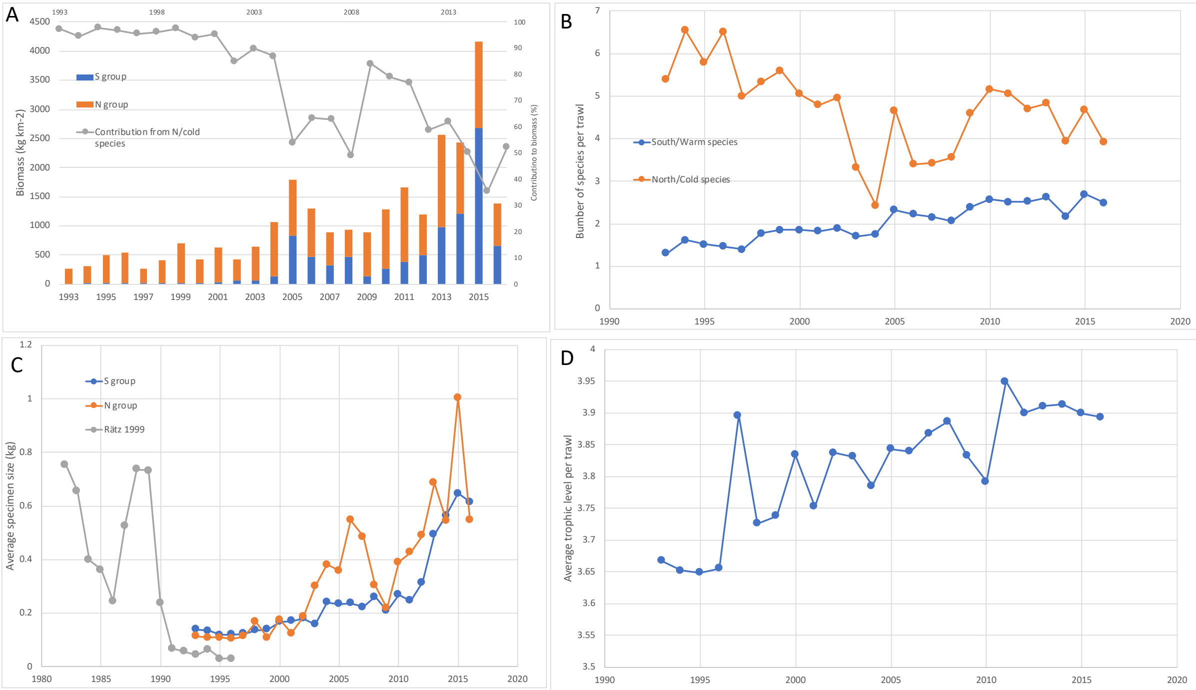


Figure 4. Changes in the demersal fish community on the West Greenland shelf and slope. A. Average biomass of warm/southern species and cold/northern species (bars) and the relative contribution of cold/northern species to total biomass (line). B. Average number of species per trawl haul separated into contribution from species with an affinity to warm/southern conditions or cold/northern. C. Change in average individual size calculated per net haul (data included from Rätz et al. 1999). D. Average trophic level per net haul.

The average trophic level for each net haul, showed a general increasing trend from about 3.65 to 3.9 (Fig. 4C). The average specimen size of both warm/south and cold/warm species increased from a stable low average of about 0.1 kg until 2004 but then increase to more than 0.5 kg at the end of the study period. We included previous size data from the region (Rätz 1999). Although, not directly comparable because it was weighted by area it does show, that the observed increase represents a return to normal. The changes in biomass, average size and average number of species where analyzed separately for the northern and southern region (north and south of 66ºN) and for the three depth strata (0-200, 200-400, and 400-600 m (Fig. S1). Increase in biomass was found in both sub-regions. In the northern region, increase in biomass in the deepest strata (400-600 m) was more pronounced than in south and in general, the highest biomass was highest in the upper 400 m. There was distinct difference in the development in average size; in the northern region, very little change was observed with increase limited to the deepest strata (400-600 m). For the average number of species, we found a slight decreasing trend about 7 to 5 species in the northern region, while the southern region did not show an overall trend, but with slightly higher richness in the upper two strata compared to the deepest during the last 8 years (Fig. S1). The change in species composition of the dominant species (by biomass) is shown in Fig. 5 where the first and last 5-year period (1993-1997 vs 2012-2016) is compared in the two sub-regions. In the northern region, we see 4-fold increase in biomass with CAP, POC and CAS being new species in the top-5 group. In the southern region, average biomass increases 10-fold, driven largely by the increase in COD biomass. In both regions, the contributions from the 5 dominant species decreased over time.

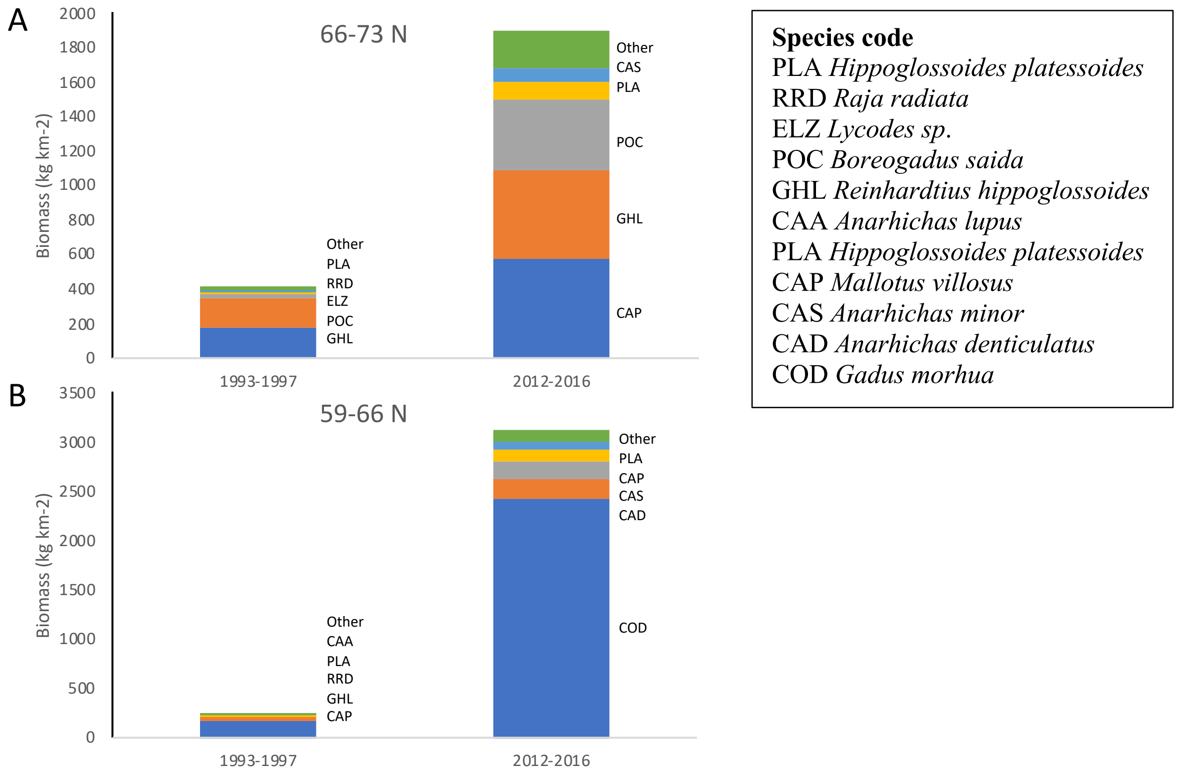


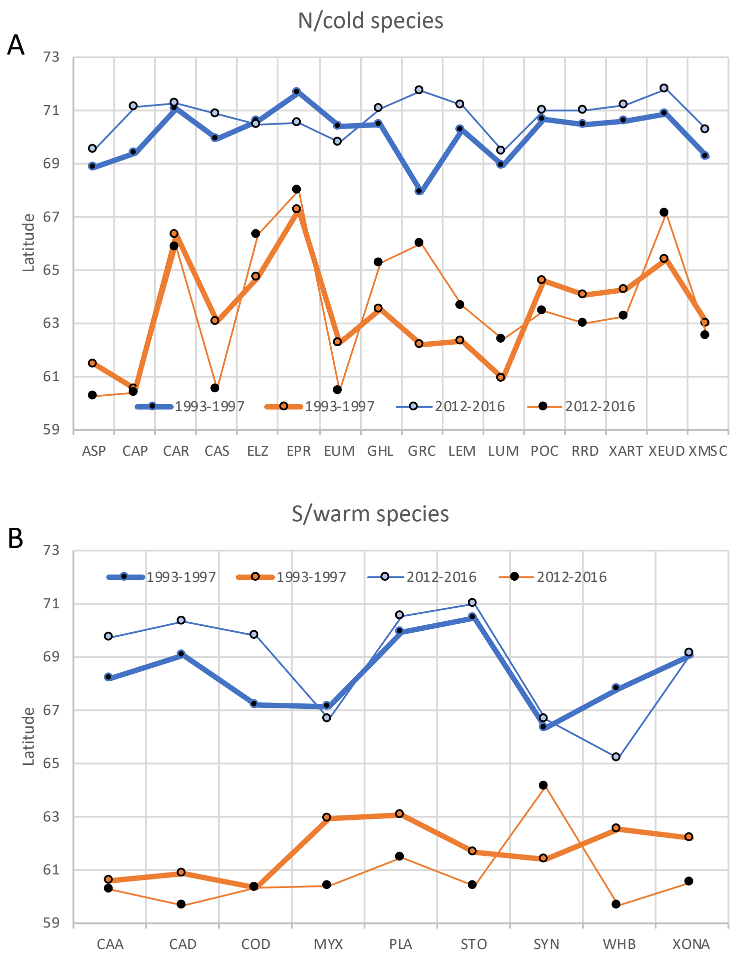
Figure 5. Changes in species composition and biomass of the 5 dominant species in the two sub-regions of the study areas

To quantify the changes in distribution of individual species across latitude, we compare the change in north and southern range expansion (calculated as the 90th and 10th percentiles of observations) between the first and last 5-year period for the two species groups; warm/south and cold/north (Fig. 6). For the cold/north group, it makes most sense to look at changes in the southern range as we assume that for most species their northern range limit is outside the study area limited to 73ºN. No consistent pattern is seen, with some species extending their range further south (CAS, EUM, POC, RRD) while some showing a retraction (GHL, GRC, LEM and LUM). For the south/warm group the change in northern range also vary between species, but with a tendency towards range expansion for 7 of 9 species.

5. Discussion

We found very extensive changes in the fish community in the study region with an increase in biomass, average individual size and trophic level combined with changes in the composition of the dominant species. The changes are most likely due to a suite of factors that vary in magnitude across latitude and species. It appears that a partial recovery of the fish stock took place. Based on independent trawl surveys, Rätz (1999) quantified demersal fish stocks in East and West Greenland 1982-1996. In West Greenland, surveys were limited to 0-400 m depth and up to 67 N. He found a 10-fold decrease in biomass and large decrease in average individual size in West Greenland and concluded that despite relatively warm bottom temperature that would favor recruitment, the spawning stock was near depletion and attributed the biomass reduction to by-catch from the expanding shrimp fisheries. Based on these data it appears that the observed increase in biomass and average size represents a return to conditions found in the mid 1980s. The commercial shrimp fishery is still extensive but in

2009 it was made mandatory to install sorting screens on trawls to minimize by-catch (GINR reference pending) which appears to have been beneficial. Also, the shrimp fishery effort has decreased and has been distributed over a slightly larger area in West Greenland (Burmeister and Rigét 2019) and is currently concentrated north of 66 N at depths between 250 and 350 m. Thus, is seems likely that fish mortality has decreased, especially in the southern part of the study are, where increase in biomass is most pronounced.



Cold/Northern species
ASP *Aspidophoroides monopterygius*
CAP *Mallotus villosus*
CAR *Careproctus reinhardti*
CAS *Anarhichas minor*
ELZ *Lycodes sp.*
EPR *Eumesogrammus praecisus*
EUM *Eumicrotremus spinosus*
GHL *Reinhardtius hippoglossoides*
GRC *Gadus ogac*
LEM *Leptoclinus maculatus*
POC *Boreogadus saida*
RRD *Raja radiata*
XART *Artediellus spp.*
XEUD *Agonidae*
XMSC *Myoxocephalus sp.*

Warm/Southern species
CAA *Anarhichas lupus*
CAD *Anarhichas denticulatus*
COD *Gadus morhua*
MYX *Myxine glutinosa*
PLA *Hippoglossoides platessoides*
STO *Stomias boa*
SYN *Synapobranchus kaupi*
WHB *Micromesistius poutassou*
XONA *Gaidropsarus spp.*

Figure 6. Changes in the northern range (90th percentile) and southern range (10th percentile) of the two species groups in the first and last 5 year periods of the study period.

The magnitude of change indicates large changes in the amount of energy going through groundfish and the trophic level and average size increase combined with shift in the dominant species especially in the southern part, also indicates large qualitative changes in how groundfish obtain energy from trophic levels below and provide energy to levels above them. With the extent of biomass change, indicating a 10-fold reduction in groundfish biomass from 1982 to 1996 (Rätz 1999) followed by a 5 to 10-fold increased from 1993 to 2016 (this study) this is likely to have cascaded to other trophic levels and caused ecosystem wide effects. Thus, the West Greenland shelf provides a good example of how long-term climate variability combines with direct impact from fisheries on shaping not only individual populations but likely the entire ecosystem. The inflow of unusual warm water of Atlantic origin in the 1930s resulted in observations of new species and changes in phenology and distribution of Arctic species (Jensen 1949). After warm and favorable conditions, the cod population increased resulting in large landing during the 1960s after which fishing mortality combined with lower temperatures in the 1980s resulted in near depletion of the population. The cold period in 1980 and early 1990 was generally assumed favorable for shrimp and led to a regime shift from cod to shrimp dominance potentially helped by the reduced predation from cod (Wieland and Hovgård 2009). As temperatures started to increase and general fish mortality appear to have decreased due to improved measures to decrease by-catch we see the recovery of fish biomass. A key question is then to what extend the recovery outcome is influenced by the warming trend. Clearly the large biomass of cod in the southern sub-region and its range expansion suggest a positive relationship to temperature and the general increasing proportion of the biomass from species with a warm and southern affinity indicates more favorable conditions for that segment of species. This also coincides with observations of new boreal species entering Greenland waters (Møller et al. 2010). In the Barents Sea, a general borealization of the ground fish community was observed as a result of increasing temperatures (Fossheim et al. 2015). A similar phenomenon driven by advection of Atlantic water happened in West Greenland in the 1930 and 1940s (Jensen, 1949) and the increase in biomass contribution from south/warm species observed from 1993 to 2016 can also be interpreted as a borealization. In general, the south/warm group of species was made up by species characterized as boreal by Fossheim et al. with the exception of CAD which we find having a warm/south affinity but is characterized as Arctic in the Barents Sea. ASP, RRD and LUM are characterized as boreal species in the Barents Sea but line up the colder/northern range of species in our study.

The recovery in biomass is dominated by the increase in warm/south affinity species, which are nearly absent in the beginning of the study period. This increase is driven primarily by the increase in Atlantic cod, which increase in abundance, biomass and northern range during the study period. The cod in W. Greenland is composed of four different stocks with spawning locations in East and West Greenland and Iceland (Bonanomi et al. 2015) and the biomass found in W Greenland is thus a product of local environmental conditions impacting the West Greenland off-shore and fjord stocks combined with interannual variation in import of egg, larvae and adults from stocks in East Greenland and Iceland (Buch et al. 2004). Additionally, West Greenland is regarded to be a nursing area for young cod which eventually migrate to spawn in East Greenland and Iceland. The increase in biomass found during 2013-2015 was based on fish of age 4-6 years but they largely disappeared in the 2016 catch, which could be due to migration (ICES 2019). The warming trend observed particularly in the two deepest strata in the northern part of our study region has most likely been favorable for severable species. In general, growth is expected to increase with temperature if there is a food supply to sustain it (Drinkwater 2005; Sünksen et al. 2010). In the northern sub-region, the biggest change is related to the large increase in capelin biomass but also of arctic cod. This is interesting because both species are key prey species for higher trophic levels of fish, bird and marine mammals and suggest a direct cascading potential to higher trophic levels.

A general poleward distributional shift is expected in temperate species as temperatures increase (Pinsky et al. 2020) and has been documented for fish in several regions. For the south/warm affinity group in this study, the response is not uniform, with only three of ten species (CAA, CAD and COD) showing increase in in northern range, whereas the total range (distance between 10th and 90th percentile) generally increased. This could indicate a density driven expansion related to the increase in biomass. For the cold/north group a northward shift of their southern range limit is observed in 6 of 16 taxa. Using the standard deviation of the temperature distribution as a measure of temperature sensitivity for each species (assuming species observed within a narrow range of temperature, and thus small SD, are sensitive to temperature changes) we find a significant correlation between SD of temperature and SD of latitudinal distribution indicating that species with a narrow temperature ranges are also tend to show less range in their latitudinal distribution.

In addition to impact from changes in advection of different water masses and the connectivity and exchange with neighboring ecosystems, the study area is also more directly impacted by climate change. Increasing air temperatures are driving reduction in sea ice cover and melting of the Greenland Ice Sheet. Sea ice cover is only significant in the northern part of our study areas with maximum seasonal coverage extending to around 69ºN (Onarheim et al. 2020). The region from about 69 to 73ºN has experienced a decrease in May sea ice concentration of about 10-15% per decade (www.NSIDC.org; Fig S2). The reduction of sea ice has been linked to increasing primary production through increased light availability (Arrigo and van Dijken 2015). For the Baffin Bay, the increase for 2003 to 2019 has been estimated at a rate of 5.5 g C m^{-2} per decade corresponding to approximately 10% (Frey et al. 2019). On the ice-free SW Greenland shelf edge during the 1998-2014 period (Tremblay and Sejr 2018) a modest increase was also found which coincides with observation of increasing chlorophyll a biomass on the West Greenland shelf and slope between 1994 and 2013 (Li and Harrison 2014). Whereas the decrease in sea ice cover primarily increase light availability, the increasing discharge in summer of melt water from marine terminating glaciers stimulates vertical mixing and nutrient replenishment (Hopwood et al. 2020) and subsequent increase in phytoplankton production. The size of glaciers and estimated sub-glacial discharge of melt water have been directly linked to the local magnitude of Greenland halibut fishery in individual fjords (Meire et al. 2017). The reduced fish mortality from the shrimp fishery thus coincides with warming in the northern region and most likely also increases in both light and nutrients to fuel primary production. Combined this may have facilitated the recovery. A borealization of the copepod community from 1992 to 2018 has been found in Disko Bay related to the decrease in sea ice cover (Møller and Nielsen 2020), indicating ecosystem changes despite the rarity of biological time series to document shifts.

Given the documented variability of the marine ecosystem off west Greenland, and the complexity of drivers involved which include targeted and non-targeted harvest, long-term variability in advection of water masses and connectivity with other regions combined with the direct impact of warming on sea ice and ice sheet melting rates pose a substantial challenge for a society that relies almost exclusively on marine living resources. Developing social–ecological resilience and successfully managing the sustainable delivery of ecosystem services requires an ability to detect causal relationships between populations and environment and react to ecological feedbacks. For the West Greenland coast and shelf, it will require an improved better dynamical understanding of food-web changes in response to multiple stressors. However, the study provides an example of how glacial and sea ice melt have increase light and nutrient availability for primary producers to facilitate recovery after improved mitigation actions to decrease by-catch. It is thus an example of how climate change may not be detrimental to the pace of recovery of exploited ecosystems.

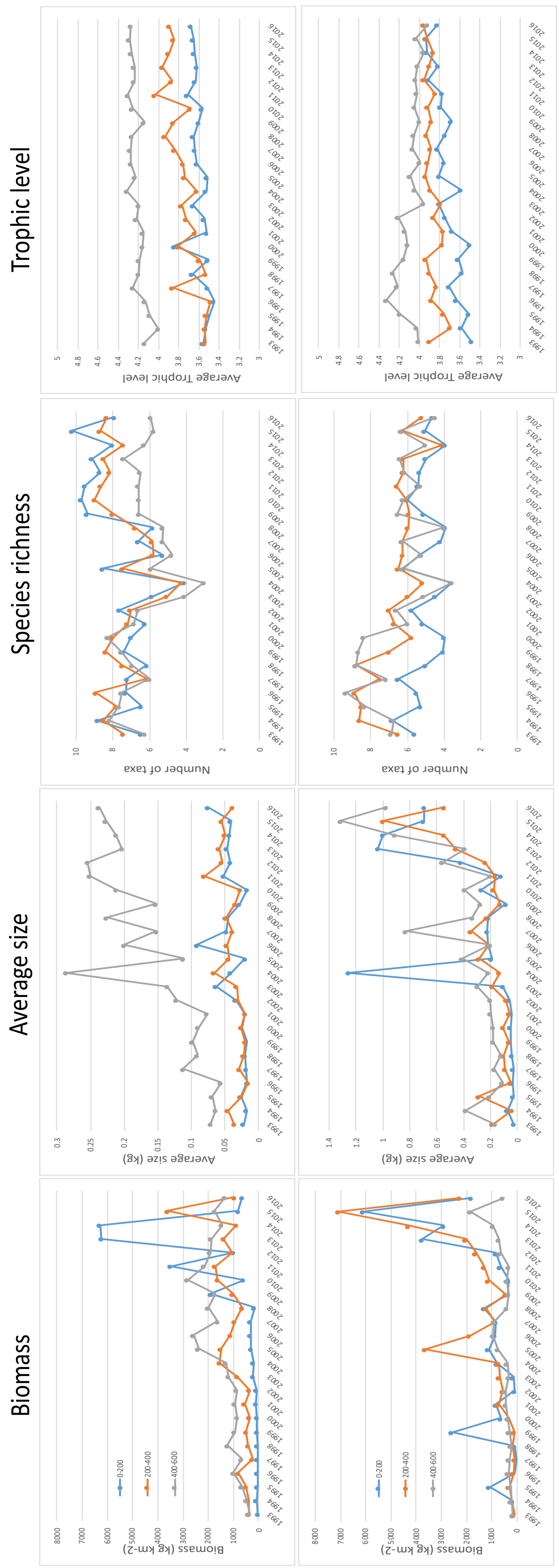

Biomass
Average size
Species richness
Trophic level
North
South
Biomass (kg km-2)
Average size (kg)
Number of taxa
Average Trophic level
0-200
200-400
400-600

Figure S1. The change in key characteristics for the dermasal fish community; biomass, average individual size and average number of species. Changes for each sub-region (north and south of 66 N) and split between the three depth strata (0-200, 200-400 and 400-600 m).

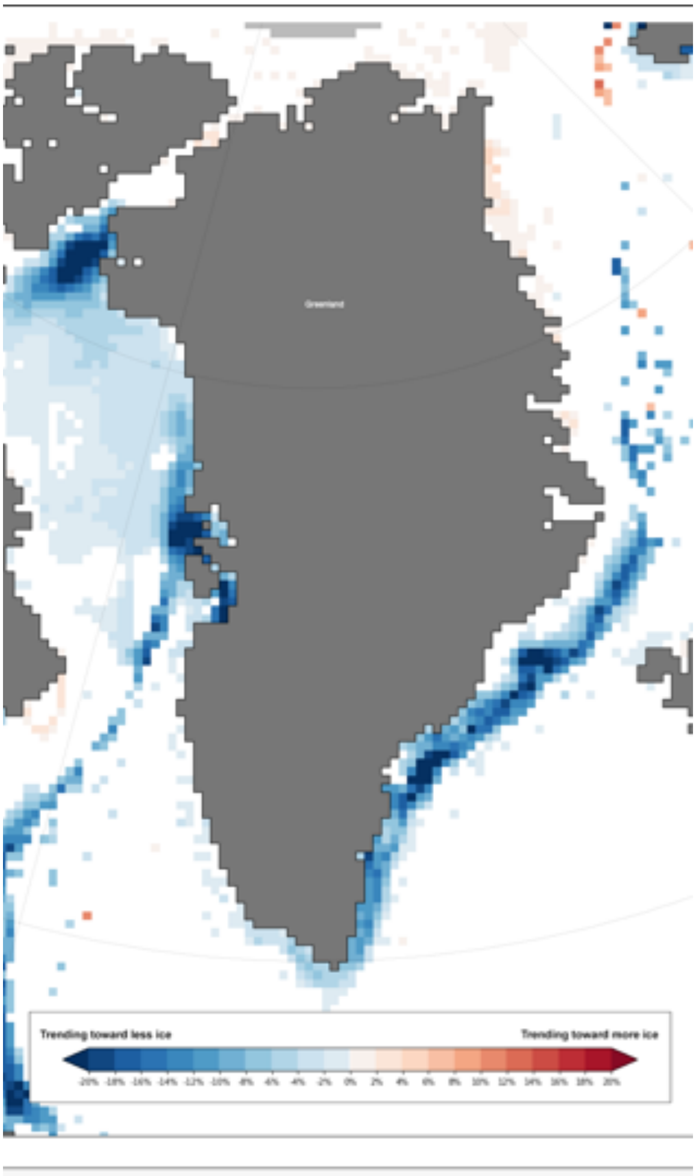


Figure S2. Trends (% per decade) in May sea ice concentration for the ocean around Greenland (1979-2020). Map produced based on data from www.NSDIC.org

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