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EXECUTIVE SUMMARY

A detailed understanding of how anthropogenic activities affect ecosystems and the services they provide is essential for sustainable management. However, assessments of the impact of multiple drivers on complex ecosystems is often challenged by lack of data at the relevant spatio-temporal resolution or knowledge of interactions among drivers.

The SW Greenland coast and shelf is important for the industrial and sustenance fishing that is essential for Greenland. Here, we aim to describe decadal changes of the ecosystem and identify key drivers. To describe ecosystem dynamics we analysed changes in the 33 species of demersal fish found in 5713 bottom trawls collected on the shelf from 1993 to 2016. We find substantial increase in average biomass combined with increases in average individual weight, average trophic level and composition of dominant species. Using previous studies as a baseline we interpret the observed changes as a partial recovery of an over-exploited system. Sea ice cover, run-off from the Greenland Ice Sheet, seafloor trawling and water mass distribution are all known drivers of ecosystem change in the study area. Although, the impact of each driver varies over the last 2-3 decades all appear to facilitate increase in fish biomass. Climate change-related melting of sea ice and the Greenland Ice Sheet likely sustained increased primary production by increasing light and nutrient availability. Increases in temperature and salinity indicates increased inflow of Atlantic water, which increase connectivity to lower latitude systems. Finally, decreased trawling effort combined with mitigation measures to decrease by-catch may have decreased fish mortality. This suggest that a combination climate change and long-term hydrographic variability may have facilitated the recovery of fish stocks. Finally, the massive changes observed in fish biomass, size and trophic level of the fish community is likely to be a strong driver for cascading effects to other components of the SW Greenland shelf ecosystem.

CONTENT

1. Introduction

Human activities are increasing pressure on ecosystems by direct harvest of living resources, fragmentation of habitats and pollution or indirectly by causing warming of the earth's atmosphere. The cumulative anthropogenic impact is thus a complex result of multiple drivers and sustainable management of ecosystems and their services thus requires detailed knowledge of both causal relationships and driver interactions resolved at both temporal and spatial scales. However, this information is incomplete for many ecosystems. The Arctic is often considered a relative pristine environment where the key drivers of ecosystem change is related to a warming climate. However, examples of overexploitation of living resources in the Arctic goes back several centuries (Weslawski et al. 2000), contaminant loads in marine mammals can be extremely high (Desforges et al., 2018) and depletion of commercial stocks occur indicating a direct human footprint on ecosystems even in this sparsely populated region.

Greenland is an Arctic nation that is dependent on its marine living resources, which constitute more than 95% of the national export and subsidence fishery is important to many Greenland households. The region is influenced by impacts of climate change which include reduction in extent and seasonal coverage of sea ice and increased summer input of melt water from the Greenland Ice Sheet, with documented impacts on the coastal ecosystem in Greenland (Meire et al., 2017). Also, the connectivity to other shelf system through ocean currents that influence the physical environment in addition to regulating the inflow of species with affinity for low latitudes have previously been shown to cause widespread changes of the West Greenland Ecosystem (Drinkwater, 2006) in the 1940s like the more recent Atlantification of the Barents Sea and it influence on fish species distributions.

In this study we analyze 24 years of data on the demersal fish community on the West Greenland shelf to quantify long-term changes. We compiled data on major direct and indirect drivers, and we relate changes in fish biomass and species composition to decadal dynamics for major ecosystem drivers in an attempt to quantify the combined anthropogenic footprint on this marine ecosystem.

2. Material and methods

Study area

The focus of this study is the SW Greenland coastal and shelf ecosystem at latitudes from 59 to 73°N. The area is characterized by numerous deep fjords connecting the Greenland Ice Sheet to the shelf. The shelf is approximately 50 km wide in the south but broadens to ca. 200 km at 73°N. Along, the shelf is a series and shallow banks, with deeper troughs in between. The local hydrography is largely determined by the two major currents The West Greenland Current and the Baffin Island Current (e.g Rysgaard et al. 2020). The West Greenland current transports warm and saline water north along the west Greenland coast. It's typically found at depth below 250 m and also provides biological connectivity to shelf ecosystems around Iceland. On top of this water mass, colder and fresher water from the Arctic Ocean, supplied by the southward flowing Baffin Island Current. Sea ice covers part of the area in winter with the typical winter sea ice extent reaching south to about 64, but with large inter-annual variability (Cavalieri & Parkinson, 2012).

Ocean temperature and salinity

We used two sources of data for describing the spatio-temporal variation in hydrographic conditions; on each trawl net-haul, a temperature sensor monitoring near-bottom temperature. Each fish observation was thus paired with a in-situ temperature. To put our temperature data and study period in a long-term perspective we analyzed depth profiles of temperature and salinity (1924-2016) from the West Greenland shelf (WGS) available at the ICES data portal (ocean.ices.dk).

Greenland Ice Sheet runoff

The meltwater runoff (1958-2016) from the Greenland ice sheet to the sea was estimated by the Danish Geological Survey for different latitudes and aggregated in two regions (59-66 °N vs 66-73 °N). The freshwater discharge originating from rain and snowmelt on land is small compared to ice meltwater (<0.1%) and was not considered

Sea ice cover

Sea ice concentrations (SIC) were downloaded (1979-2016) from the National Snow and Ice Data Center and aggregated into two shelf regions (59-66 °N and 66-73 °N). We focused on ice condition during spring (April and May) to highlight changes that influence light availability for marine primary production.

Shrimp trawl effort

To quantify the potential impact from shrimp trawling we compiled data on reported trawl effort (reported as hours trawling for individual ships). Total hours of combined trawling efforts were aggregated to two areas; (59-66 °N and 66-73 °N).

Demersal fish

Abundance and weight for 33 key species were recorded from 5713 net trawls along the shelf bottom based on the annual surveys (1993-2016) conducted by the Greenland Institute of Natural Resources along the West Greenland Shelf (59.44-73 °N). The trawls swept an area ranging from 0.01 to 0.17 km^2 and depths ranging from 25 to 600 m. Two different net types with same mesh size (20 mm) were employed over the study period shifting from SK30 (1993-2005) to CO26 (2004-2016), but an intercomparison employing both net types in parallel during surveys in 2004 and 2005 suggested no or minor difference. A temperature logger was attached to the net starting from 1995, recording the temperature associated with the trawl. All trawling were associated to northern (66-73 °N) and southern region (59-66 °N). Over the 24-year study period, the annual number of surveys increased (Fig. S1A), surveys started earlier in the season (Fig. S1B), expanded slightly to the north and south (Fig. S1C), the average depth of net trawls decreased slightly in both regions (Fig. S1D), and the swept area decreased (Fig. 1E) as the overall biomass started to increase (Fig. 2B), whereas average temperature of the samples remained relatively constant although with some interannual excursions (Fig. S1F). For each species a trophic index was assigned based on species specific information found in FishBase. For some species where identification to species level can be problematic, species was pooled to genus or family level.

Statistical analyses

Trends in salinity and temperature were calculated for five different depth strata (0-50, 50-100, 100-200, 200-400, and 400-600 m) using a General Linear Model (GLM) describing variations among years, months and hydrographical areas as categorical factors (Carstensen et al. 2006). The GLM approach accounts for the temporal and spatial heterogeneity of the data, and marginal means for the year factor provide trend estimates unaffected by seasonal and spatial variability in the samples.

Total biomass of the 33 key species, average weight and trophic index of individuals caught in each trawl were investigated in relation to sampling latitude, depth and temperature for each year and region separately using Generalized Additive Models (GAM) (Fig. S2-S4). These showed clear and consistent relationships with depth and latitude, whereas relationships with temperature were ambiguous and, in many cases, not significant (Fig. S5). Therefore, for calculating trends in total biomass, average weight and trophic index, taking differences in sampling latitude and depth into account, a semi-parametric GAM model was employed

$$E[y_{ijk}] = \mu + region_i \times year_j + S(latitude_{ijk}) + S(depth_{ijk}) \qquad \text{(Eq. 1)}$$

where y_{ijk} denotes either log(total biomass), log(average weight) or average trophic index, $region_i \times year_j$ describes region-specific trends, $S(latitude_{ijk})$ is a non-parametric common relationship with latitude, and $S(depth_{ijk})$ is a non-parametric common relationship with depth. The inclusion of the two spline functions ensures that the region-specific trends are unbiased with respect to changes in sampling latitude and depth across years. The region-specific trends were predicted and displayed for average sampling latitude (68.79 and 62.45 °N for region North and South, respectively) and depth (306 and 243 m for region North and South, respectively) across all years.

Species-specific counts and weights were analyzed within the framework of Generalized Linear Models (GLM) a parametric model that used either sampling latitude, depth, or temperature as explanatory variable (x) in addition to region-specific trends to describe variations in the mean value through a link function ($g()$), i.e.

$$g(\mu_{ijk}) = region_i \times year_j + b \cdot x_{ijk} + c \cdot x_{ijk}^2 \qquad \text{(Eq. 2)}$$

Species-specific counts were modelled as a Zero-Inflated Poisson (ZIP) distribution with log of swept area as offset variable to account for the variable trawl effort, whereas weight was modelled as a Gaussian distribution. The log link function was used for the Poisson and Gaussian distributions, and the logit link function was used for the Bernoulli distribution describing the zero-inflation. Thus, the same generic model (Eq. 2) was used to describe counts as Poisson distribution, zero inflation as Bernoulli distribution and weight as normal distribution for each species. The model included only one of the three explanatory variables at a time, since the number of observations with positive counts and weights was low for several species, restricting the possibility to identify relationships with multiple explanatory factors simultaneously. Consequently, regional trends were estimated for each of the three models using either sampling latitude, depth, or temperature as x in Eq. (2), and subsequently averaged to produce common regional trends for abundance and weight for each of the 33 key species.

The two last terms in Eq. (2) describe a parabolic relationship with respect to the explanatory variable x, and these relationships were used to identify the maximum expected abundance for each species and the corresponding optimum conditions for latitude, depth, and temperature (Fig. S6). Optimal ranges for the explanatory variables were calculated for latitude, depth and temperature, where the expected abundance was at least 5% of the optimum value. Region-specific trends for species' abundance and weight were related to optimum conditions for latitude, depth, and temperature as well as average weight to investigate the specific characteristics of species with changing abundance and weight.

3. Results

Hydrography

The distribution of the trawl 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). It can also be seen that maximum temperatures are found at bottom depths of 100-200 m (Fig 1C). 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).

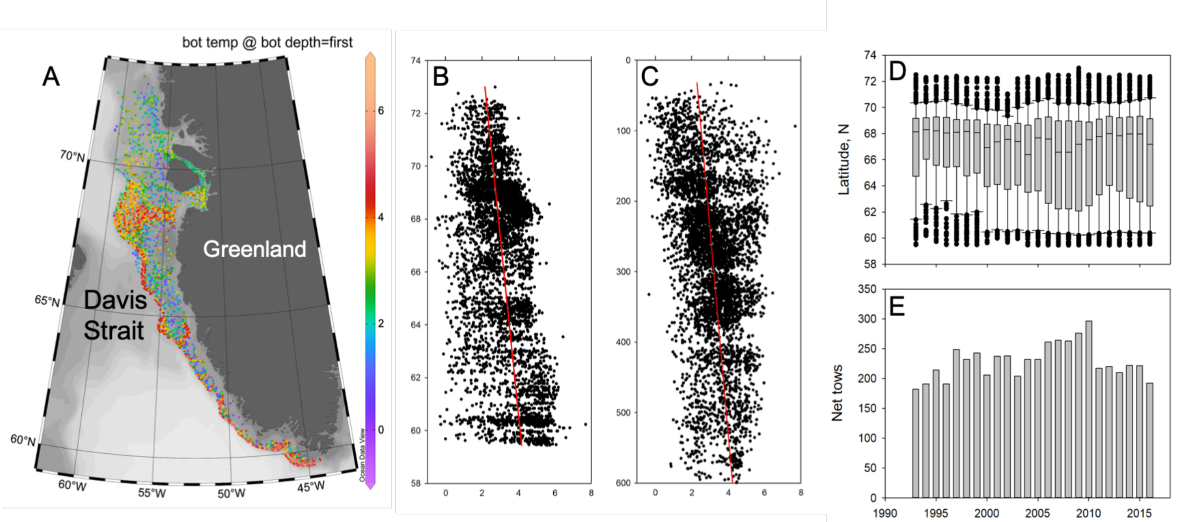
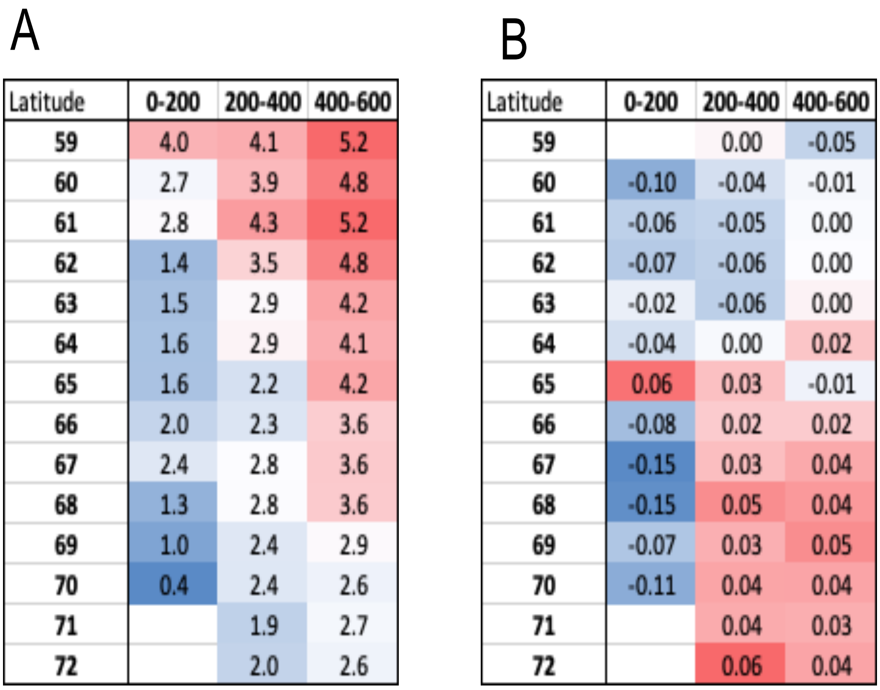


Figure 1. A. Study area with each trawl haul and the corresponding bottom temperature. B. Distribution of summer bottom temperatures across the study area. C. Distribution of bottom temperatures as a function of depth. D. Box plots of the latitudinal distribution of trawl hauls each year. E. Total number of hauls each year.

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 66° N.



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. The average bottom temperature (1993-2016) measured at different depth intervals for 1° latitudinal segments. B. Linear trend in temperature at each latitudinal segment and for each of the three depth intervals.

To put our temperature data and study period in a long-term perspective we analyzed summer CTD data from the region. 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.

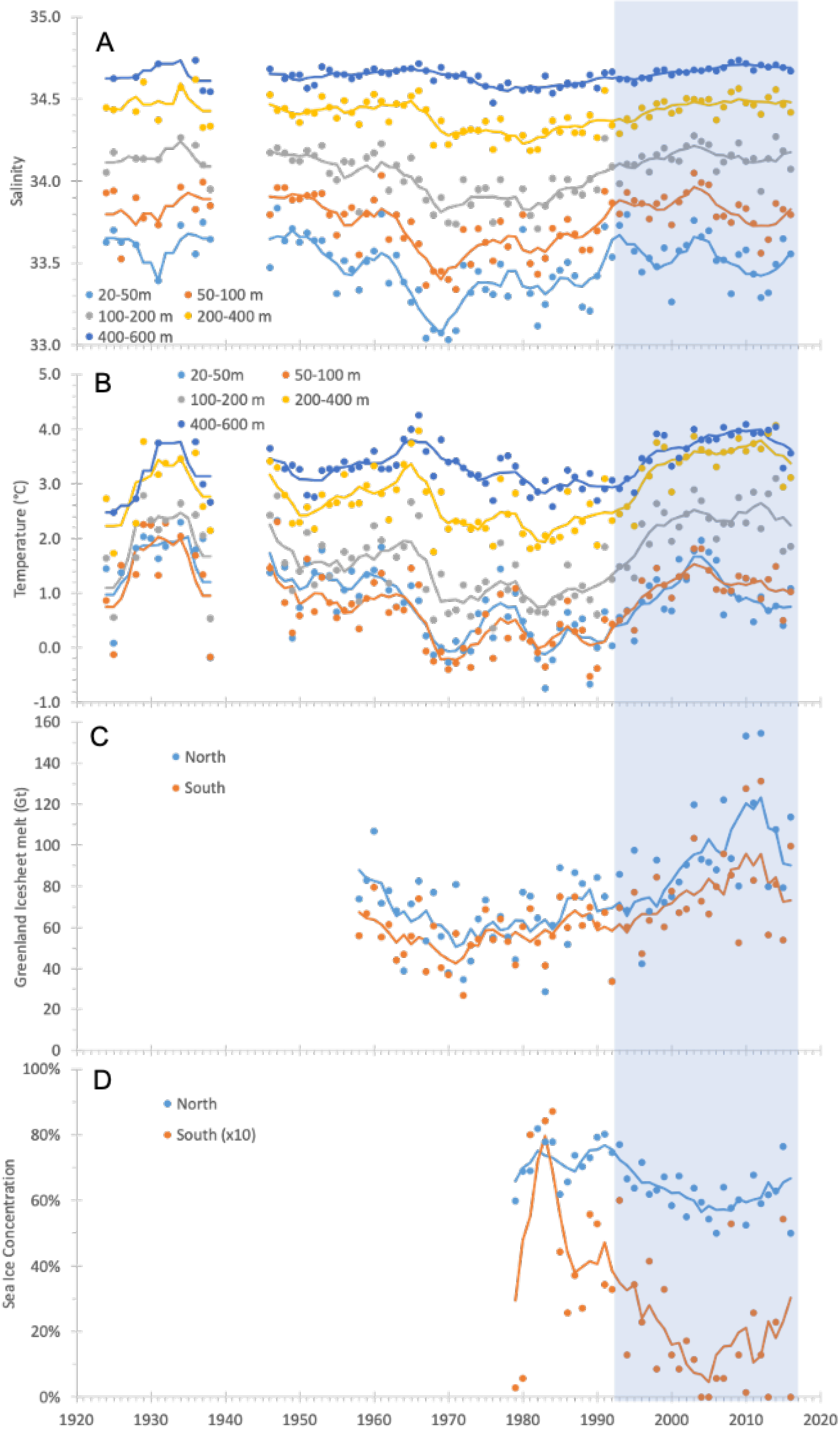
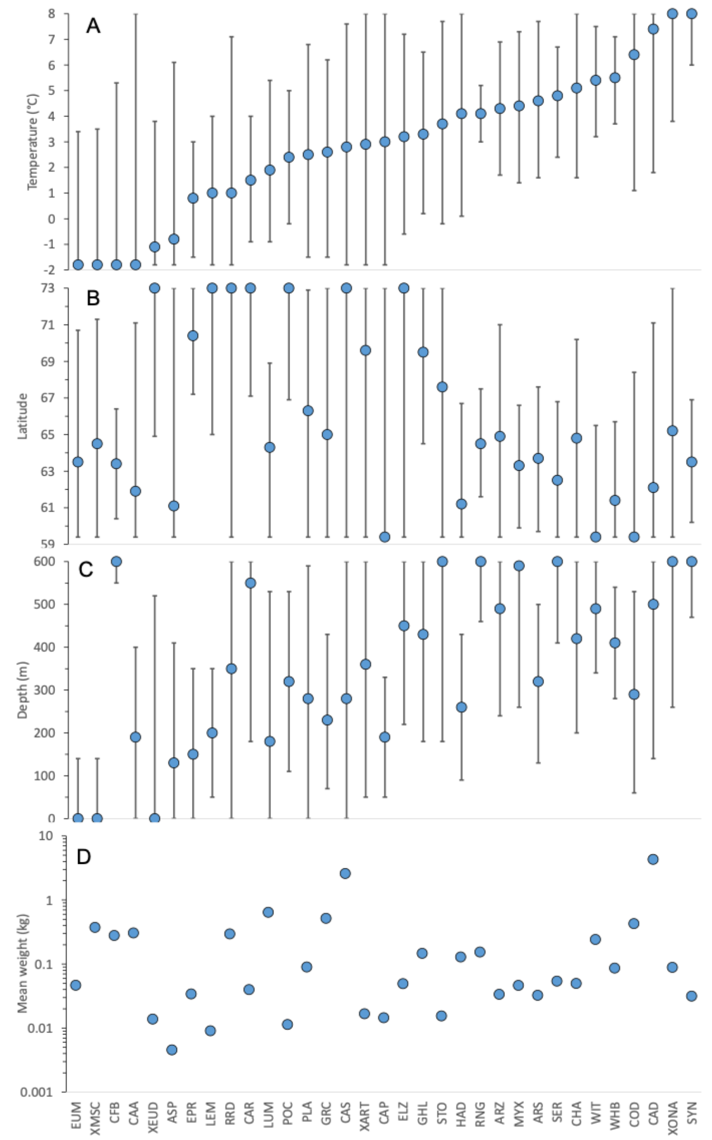


Figure 3. A. Long-term variability on SW Greenland shelf salinity based on CTD data from open data repositories. B. Changes in temperature. C. Variation in melt water run-off from the Greenland Ice Sheet. Data aggregated for the southern (59-66☐ N) northern (66-73) part of the study area. D. Interannual variation in average April and May sea ice cover for the southern and northern part of the study area.

Sea ice

The average sea ice cover in April and May showed that the marginal sea ice zone in spring is found between 67-68 °N. This means that the average sea ice cover in the southern part of the study area is below 10%, whereas its 60-80% north of 66 N. In the northern region there is a decreasing trend from nearly 80% ice cover in the 1980s to less than 60% ice cover in 2007, but with increasing ice cover found from 2007-2015 (Fig. 3D)



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

Figure 4. A. Optimum temperature (± standard deviation) for demersal fish on the SW Greenland shelf based on trawl mounted temperature sensors. B. Latitudinal distribution (± standard deviation). C. Depth distribution. D. Average individual weight of each species. The code for the abbreviation used and scientific and common names are given in the table to the right.

Ice Sheet Run-off

The modelled run-off from the Greenland Ice sheet for the southern and northern region of our study area is fairly similar and show the same temporal trend. During the 1960s there is a general decrease in run-off that reaches a minimum around 1970 (Fig. 3C). This is followed by a steady increase spanning 40 years, but with a tendency towards a drop during the last 2-3 years of the time series. The increase in run-off is slightly more pronounced for the northern region, where the increase approaches a doubling compared to values in the 1970.

Trawl effort

The combined trawl effort in the study area was quantified annually from 1993 to 2016. In the beginning of the 1990s the trawl effort was equally distributed between the two regions, this changes during the late 1990s where effort in the southern region started to decrease. Across the study period trawl effort in the north stay relatively stable with 60.000 to 80.000 trawl hours per year, whereas the southern regions sees a significant drop from 80.000 to less than 10.000 hours per year.

Fish data

We quantified the physical niche of each species by estimating their optimum latitude, depth and temperature (Fig. 4). The distribution along a gradient with their optimum temperature (Fig. 4A) can be used to categorize species into those with an affinity to the cold (< 0°C) or warm (>5°C) end of the temperature range found in the study area. The standard deviation from the optimum temperature can be interpreted as a measure of how temperature specific or tolerant each species is. Lowest temperature optimum was found for the lumpsucher, while highest optimum was for Kaup's arrowtoothed eel. It is also apparent that the temperature preference of each species not necessarily corresponds to latitude ie species with an affinition for low water temperature are not limited to the northern part of the study area (Fig. 4B). Instead, species' temperature preference aligns with their depth preference, so that species with an affinity for low temperature are found in the upper ~200 m (Fig 4C) corresponding to the vertical distribution of temperature. However, the species with temperature optimums >3 C, are primarily found in the southern part of study region.

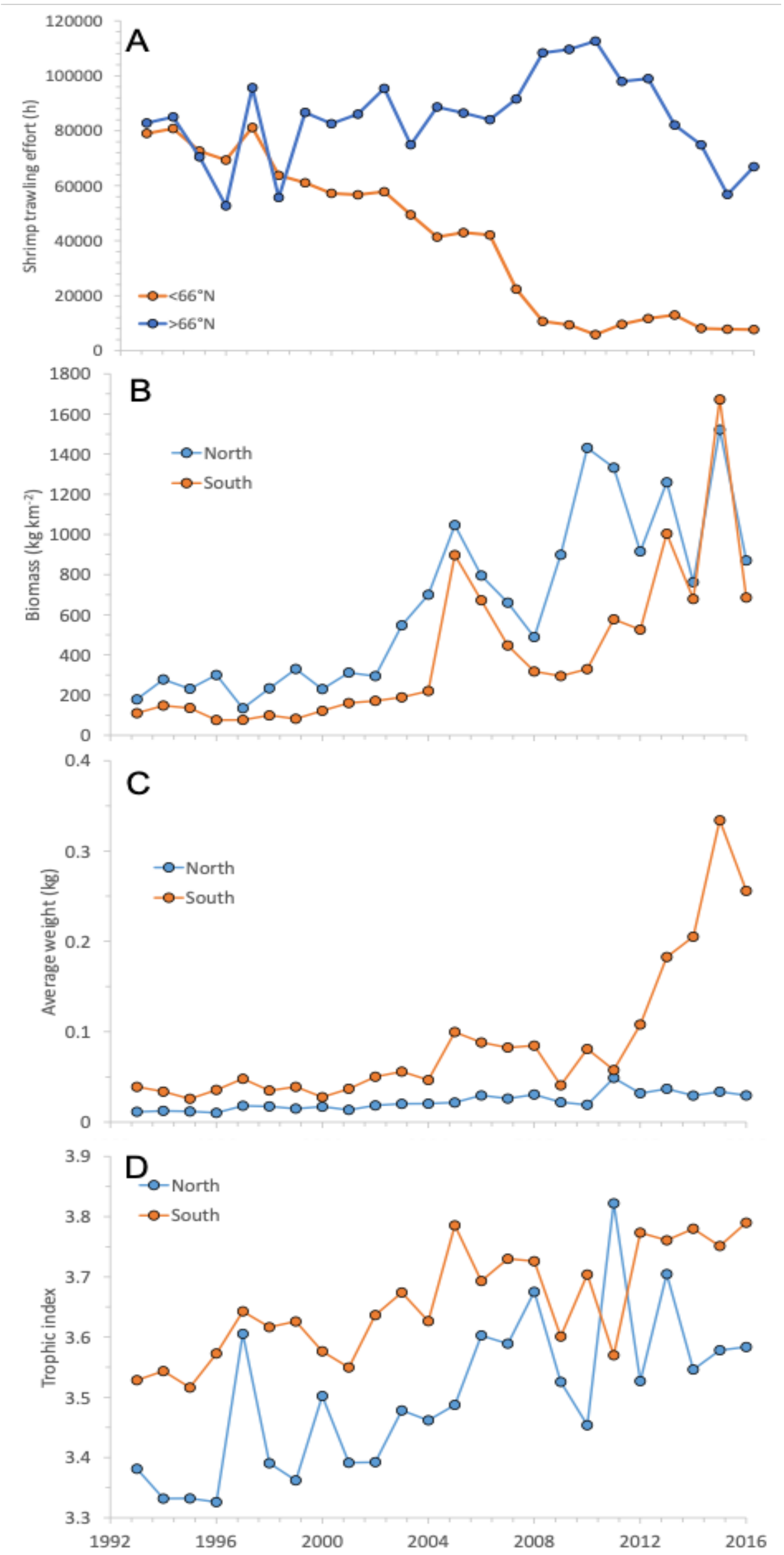


Figure 5. A. The combined shrimp trawling effort on the SW Greenland Shelf (from 59 -73°N), aggregated to the northern and southern part of the area. B. The average demersal fish biomass estimated from the summer trawl hauls for each sub-region in the study area. C. The average individual weight per individual in the net hauls. D. The estimated average trophic level of demersal fish in the net hauls.

The biomass of demersal fish increase during the study period. In both the northern and southern part of the study area average biomass was relatively stable from 1993 about 2001 with biomass slightly higher in the north than in the south. Then biomass increase in 2004 across the study areas with a second spike around 2010 where biomasses increase to more than 1000 kg km-2 or 5-10 fold above the initial values (Fig. 5B). The increase in biomass is accompanied by an increase in average individual size for several species as well as an increase in the average trophic level of the dermasal fish community (Fig. 5CD). When comparing the total biomass and the dominant species in the first five years against the last five years it can be seen that the increase in average biomass is largest in the southern part of the study (Fig. 6). Of the five dominant species only two species remain dominant; Capelin and American plaice, whereas Atlantic cod is the dominant species contributing to the increase in biomass. In the northern region, Capelin, Greenland Halibut and Polar cod all contribute equally to the biomass increase.

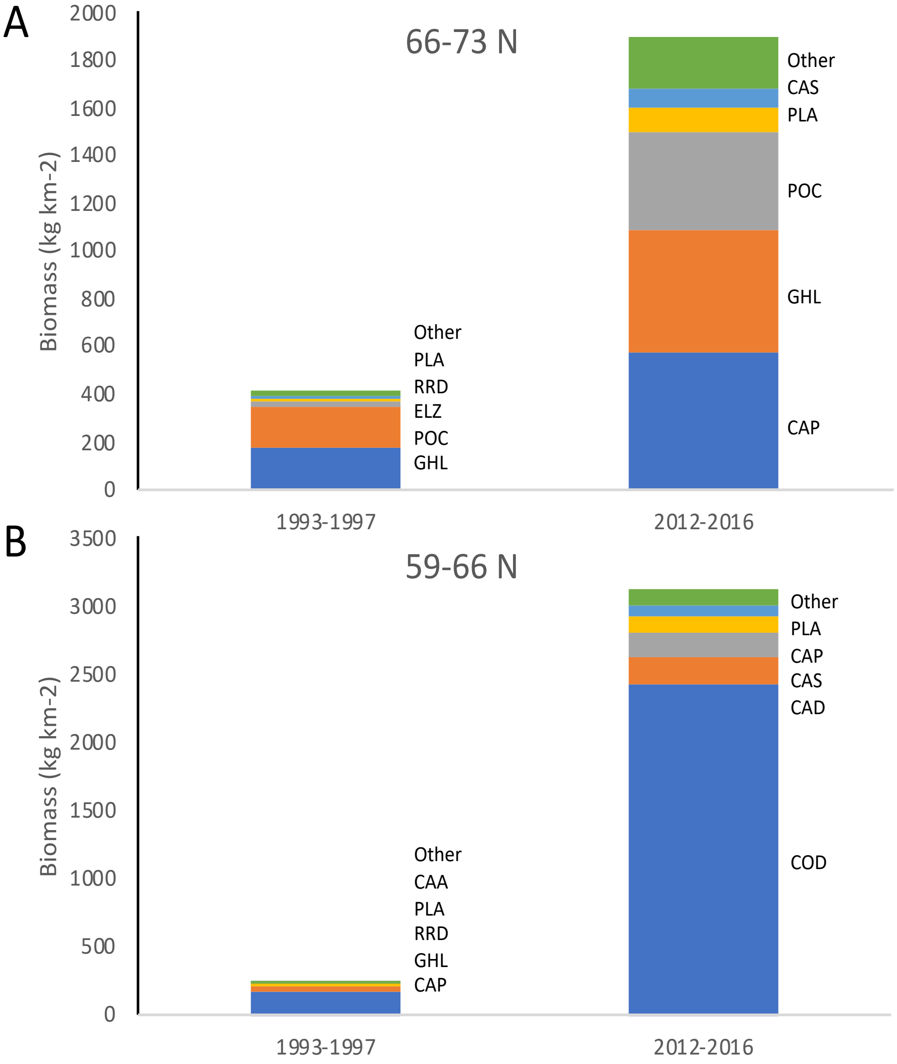


Figure 6. A. Changes in species composition and biomass of the 5 dominant species in the northern and B. southern part of the study areas. See Figure 4 for species code.

4. Discussion

In this study, we quantify changes of the demersal fish community during 1993 to 2016 on the SW Greenland shelf. This data set is one of the most comprehensive biological data sets from the region and we aim to use dynamics of the demersal fish community as a proxy for changes in the general shelf ecosystem in order to explore links to potential ecosystem drivers such water mass distribution and temperature, sea ice cover, trawl impact and run-off from the Greenland Ice Sheet.

We found extensive changes in the fish community, with an increase in biomass, average individual weight and trophic level combined with changes in the composition of the dominant species. It appears that a partial recovery of the fish stock took place. Based on independent trawl surveys, Rätz (1999) quantified changes in demersal fish biomass from 1982 to 1996. In West Greenland, he found a 10-fold decrease in biomass and large decrease in average individual weight 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 total biomass and average individual weight found in our study 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), and the increase in biomass in the northern region despite a constant trawl effort suggest this could 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.

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 (Bonanomi et al. 2015). 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 & 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 suggests 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 (P. R. 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, Stenberg, & Grønkjær, 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.

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, Eldevik, Smedsrud, & Stroeve, n.d.). 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 & 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, Comiso, Cooper, Grebmeier, & Stock, 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 & 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 (E. F. Møller & 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 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 increased 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.

5. Conclusion

The analysis presented here is the first attempt at a synoptic ecosystem study of the factors that influence fish stock dynamics on the West Greenland Shelf. The immediate goal is to have the analysis quality controlled through submission to a peer-reviewed scientific journal. The main findings have been presented at a workshop with Greenlandic stakeholders, (described in detail in D6.2) which resulted in an interesting discussion about how to integrate other data resources into the stock assessment and fishery management in the region. The collaborative study with managers in Greenland directly demonstrated that relevant environmental data from a variety of sources (modelling, open data repositories and remote sensing) can be combined with *in situ* biological observations. This study thus contributes to the INTAROS roadmap by summarizing data from operational observation systems in the eastern Baffin Bay and Davis Strait region, and exemplifing how data can be made available and relevant for managers. Additionally, we identified a specific end-user need (an integrated analysis of decadal scale temperature changes on the SW Greenland shelf) and initiated the required analysis through a demonstration project in WP6.

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