Loss of pelagic fish and zooplankton density associated with subglacial upwelling in high Arctic estuaries may be mitigated by benthic habitat expansion following tidewater glacier retreat

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Abstract

Glacier fronts are hotspots of pelagic productivity due to upwelling of nutrient-rich water. As tidewater glaciers retreat into land, this subglacial circulation will disappear and sedimentation from terrestrial runoff will increase, leading to a decrease in pelagic productivity with a decline in the abundance of fish and zooplankton. We used Billefjorden, a high Arctic fjord with a glacier recently transitioned from sea- to land-terminating as a case study to identify spatial differences and small-scale environmental drivers of density and vertical distribution of fish and zooplankton along a gradient of glacier retreat (directly in front of the land-terminating glacier front, a river bay with terrestrial input from land-terminating glaciers further inland and a location with minimal glacial input). We developed a sustainable and efficient protocol to safely sample the glacier front and shallow coastal areas using hydroacoustics and a remote autonomous vehicle combined with oceanographic measurements and baited remote cameras. Over two years, pelagic density was lowest at the now land-terminating glacier front and highest at the site with lowest terrestrial input. Temperature, depth and turbidity explained less than 8% of the variation each. The site with the least glacial input had the most heterogenous bottom habitat due to the presence of kelp forests, and the richer demersal habitat likely contributed to the higher pelagic density. In shallow fjords and areas with hard bottom substrate, it is expected that sea-ice and glacial retreat will promote macroalgal settlement, and we suggest that macroalgal expansion may compensate the loss of tidewater glacier-associated density of fish and zooplankton by the increase of benthic-driven density. Arctic pelagic ecosystems could thus be more resilient to glacier retreat than initially thought, but this is highly dependent on fjord topography, sedimentation rate and substrate type. Our developed protocol is an efficient non-invasive method to survey shallow coastal areas and glacier fronts in the Arctic.

Keywords

Kelp forest, glaciers, fish, zooplankton, Svalbard, acoustics, climate change

1. Introduction

The impacts of global warming and climate change have been widely studied on offshore shelves and in the open ocean, but knowledge gaps persist with respect to nearshore coastal areas and within Arctic fjords and glacier fronts. The effects of retreating tidewater glaciers on fish distribution remain particularly understudied, as they are areas under rapid change and very challenging to access and monitor. The high abundance and biomass of zooplankton in glacier plumes suggest that glacier fronts may serve as refugia for zooplankton-dependent food webs (Hop et al., 2023), and are important feeding areas for key Arctic fish species such as polar cod (*Boreogadus saida*) (Lydersen et al., 2014; Renaud et al., 2012). Upwelling from tidewater glaciers, caused by subglacial freshwater discharge that rises to the surface, circulates nutrient-rich bottom waters and replenishes zooplankton and juvenile fish to the surface waters, making these areas highly productive hotspots for fish, marine mammals, and seabirds (Lydersen et al., 2014; Vonnahme et al., 2021). It has been suggested that these areas provide refugia for Arctic species due to enhanced prey availability, as access to other feeding areas such as the marginal ice zone becomes more energetically demanding as the ice edge retreats (Hop et al., 2023; Varpe & Gabrielsen, 2022). As glaciers retreat, these refugia are getting fewer and smaller but further research is needed to study how pelagic organisms will react to these changes in littoral fjord areas.

Despite a shift from tidewater glaciers to land-terminating glaciers, significant amounts of nutrients can nonetheless be brought into the sea through terrestrial runoff, groundwater discharge and permafrost thawing (Holmes et al., 2008; Terhaar et al., 2021), which are increasing due to higher precipitation and melting rates (Nowak et al., 2021). However, the associated high sediment and freshwater input leads to higher stratification and light attenuation in the water column that inhibit primary production at a local scale (Connolly et al., 2020; Halbach et al., 2019), and hence the transition from tidewater to land-terminating glaciers is expected to negatively affect pelagic productivity in Arctic fjords (Hopwood et al., 2020). Conversely, the retreat of tidewater glaciers and sea ice is opening new areas where macroalgae can potentially settle and drive benthic primary production (Assis et al., 2022; Krause-Jensen & Duarte, 2014), which may offset the loss of production from tidewater glacier retreat and associated glacial upwelling. In deep fjords and coastal areas where sediment runoff is increasing from land-terminating glaciers, macroalgal settlement may be inhibited due to low light penetration and unsuitable settling substrate, but these interactions are highly dependent on fjord topography and bottom substrate type. Macroalgae are ecosystem engineers and provide important feeding and nursing sites for fish and benthic fauna (James & Whitfield, 2023; Lippert et al., 2001), and a macroalgal expansion in the Arctic is expected to provide opportunities for associated species (Włodarska-Kowalczuk et al., 2009). The interactions of glacial discharge with the marine coastal ecosystem are complex, as there are several concomitant and occasionally counteracting effects, and little empirical data exist on the transition from a rich tidewater glacier front to a land-terminating glacier system, and particularly to what extent this will affect fish and zooplankton communities in these areas.

Pelagic ecosystems at glacier fronts and shallow nearshore areas are challenging to study with traditional sampling (e.g. gillnets, trawls) due to risks from drift ice, shallow rock formations and difficulties operating vessels close to shore. Furthermore, these techniques have inherent biases such as size and species selectivity and are invasive (e.g. bycatch and damage to the seafloor). For this reason, coastal fish communities in Arctic fjords and their responses to glacier retreat are understudied. Developing a methodology to efficiently and sustainably study fish and zooplankton dynamics in these areas may provide a valuable link between the effects of glacier retreat on marine biogeochemistry and primary production and changes in fish and zooplankton communities and distribution. Alternative methods such as autonomous vehicles and hydroacoustics are emerging as a sustainable and non-invasive method for ecological monitoring in the Arctic (e.g. Dunn et al., 2023; Geoffroy et al., 2016). Though active acoustics are often used in conjunction with net sampling in order to achieve higher taxonomic resolution and for ground truthing (Simmonds & MacLennan, 2005), scientific echosounders can be used as a standalone tool to record acoustic backscatter as a proxy for density as well as vertical distribution patterns (Axenrot et al., 2004; Kaartvedt et al., 2009).

The aim of this study was to compare areas along a gradient of glacier retreat, from a very recently transitioned glacier front from tidewater to land-terminating, a bay heavily affected by land-terminating glaciers further inland to a site where glaciers have been absent for a long period of time. Specifically, the density and vertical distribution of fish and zooplankton were compared between the three study locations. Comparing different environmental conditions within a single fjord provided a natural laboratory from which to measure the impacts from different physical environmental parameters linked to glacier retreat and, ultimately, how it could apply to large-scale modifications to the cryosphere. We hypothesized that land and glacial run-off at the river bay and land-terminating glacier front, with high sedimentation rates and low light availability for primary producers, leads to an area with low productivity and low biomass of zooplankton and fish. Furthermore, we developed and present a protocol to study pelagic ecosystems in coastal and glacier front habitats in the Arctic using a novel, cost-efficient and non-invasive technology.

2. Materials and methods

2.1 Study area

We conducted this study in Billefjorden, a high Arctic fjord located in Spitsbergen, Svalbard in September 2021, August 2022 and August 2023. Billefjorden is characterized by a shallow sill (70 m depth) at the fjord mouth which limits the inflow of Atlantic water from the West Spitsbergen current that normally flows into the western fjords in Svalbard (Fig 1A). This allows Billefjorden to stay colder than the surrounding fjords (Nilsen et al., 2008). Billefjorden has a heterogenous coastscape with a large river bay and the glacier Nordenskiöldbreen located at the inner part of the fjord (Fig 1B). This originally marine-terminating glacier has been retreating rapidly and the northern side is now mostly land-terminating since 2017 (Kavan et al., 2023; Szczuciński et al., 2009). Petuniabukta, located northwest from the glacier, gathers a high amount of sediment run-off from the surrounding valleys and land-terminating glaciers through rivers (Láska et al., 2012) which creates a river bay with a large tidal flat. Glacial freshwater input from rivers and the sediment plume of the Nordenskiöldbreen glacier decrease with distance from both the river bay and the Nordenskiöldbreen glacier bay, and becomes minimal in the middle of the fjord, where the glacier front retreated 11,000 years ago (Baeten et al., 2010). This allows for a natural laboratory and the systematic comparison between the recently land-terminating glacier site (GLA), the river bay (RIV) with inland glacier-derived river input, and a site with minimal glacial input that can be considered practically as a control site for glacial influence (CON) (Fig 1B).

2.2 Survey design

At each of the three stations (RIV, GLA and CON), pelagic backscatter, a proxy for density of pelagic organisms, was measured via active acoustic mapping with a downward facing BioSonics DTX scientific split-beam echosounder (BioSonics, Seattle, USA) mounted to the rear of an Uncrewed Surface Vehicle (USV). Hydroacoustics is commonly used as a method to study fish and zooplankton, as these organisms scatter sound due to the contrast between their morphological properties (e.g. gas-filled structures and hard exoskeletons) and the surrounding water (Simmonds & MacLennan, 2005; Stanton et al., 1996). Metrics of acoustic backscatter were recorded to quantify abundance and density of fish and zooplankton in the water column. We used an Otter USV (Maritime Robotics, Trondheim, Norway), an electric 200 x 108 x 106 cm vehicle which was controlled remotely via broadband communication radio (Direct link 5150 – 5875 MHz) from a nearby ship. The echosounder was used at an operating frequency of 200 kHz, which is commonly used to detect and study fish and zooplankton (Simmonds & MacLennan, 2005), a ping rate of 5 Hz and pulse duration of 0.4 ms. Georeferencing of the acoustic data was done through the USV’s internal Global Navigation Satellite System (GNSS). Hydroacoustic mapping was done by running the USV in transects at an approximate speed of 3 knots perpendicular to the shoreline twice, in August 2022 and August 2023. The middle points of the transects were between 200 m and 800 m away from shore and with an average of 30 m water depth at all sites, with all stations covering the minimum range of 24 m to 42 m depth. In 2022, the transects were 17 minutes long covering an area of 2.8 ha and were done 6 times at each station (Supplementary fig 1). In 2023, the sampling area was increased for each station to 8.5 ha and 45 minutes long transects by increasing the number of transect lines and were conducted 2 times. Each time the transects were run is considered a replicate (6 replicates in 2022 and 2 replicates in 2023).

To characterize the physical environment, oceanographic data were collected via a Valeport SWiFT CTDplus with Turbidity (Valeport Ltd., Totnes, UK). CTD water column deployments were conducted from the ship to record temperature (degrees Celsius), salinity and turbidity (nephelometric turbidity units; ntu) before the acoustic surveys. CTD profiles were taken for the entire water column (surface down to bottom depth) at the three stations in both years. The CTD deployments were taken at approximately 200 m from the center of the acoustic transects. These data were recorded to broadly characterize and compare the different study sites, as a high-resolution description of the oceanography of these areas would require a more comprehensive survey. Temperature and salinity profiles were also used to calculate the speed of sound and coefficients of absorption to calibrate the acoustic data.

To document the benthic habitat and bottom substrate type, baited remote underwater video deployments (BRUV) were done once at each of the stations in September 2021. The BRUV rig consisted of a metal frame with a GoPro camera and a 1 m- long arm holding a mesh bag with 1 kg of polar cod (*Boreogadus saida*) as bait. The BRUV was lowered to the bottom at a depth of 10 m and recorded video for 1 hour at each station. The maximum number of individuals observed at the same time at any one time on the entire video (MaxN) was used as a measure of relative abundance of taxa, which is commonly used in BRUV analyses to avoid double-counting (Osgood et al., 2019).

2.3 Hydroacoustic analyses

All raw acoustic files were extracted from the USV system and merged to create a single file for each station using Visual Acquisition v6.4.1.12747 (BioSonics, Seattle, USA). Acoustic data were subsequently processed in Echoview 13.1.121 (Echoview Software Pty Ltd, Tasmania, Australia). For each station, the file was scrutinized for noise and a bottom line was set by using the "Best bottom candidate" algorithm. A smoothing filter was applied to correct for benthic fish merging with the bottom signal, and very minor manual editing was done to correct for gaps in the bottom line when the signal momentarily dropped below the threshold. An exclusion line was added at a fixed depth of 5 m to exclude near field region noise close to the transducer, as well as a line 1 m above the bottom to exclude bottom noise, and the analyses were limited to the water column in between the exclusion lines.

To study variability in pelagic density between replicates for each station, each replicate of the 2022 data were then divided in 1-minute long echointegration cells, for a total of 17 grids (as each run was 17 minutes long), and the integrated volume backscattering strength (Sv in the logarithmic form dB), center of mass (in m) and inertia (in m^2) for each cell were exported for further processing and analyses in the R statistical software v4.1.2 (R Core Team, 2021). Volume backscattering strength (Sv) is a proxy for the density of organisms, center of mass identifies the average backscattering depth in the water column, and inertia is a measure of the spatial dispersion of scatterers around their center of mass (Urmy et al., 2012). A low inertia indicates tightly packed scatterers, while a high inertia indicates a larger spread.

The acoustic data was also exported as one file per replicate and the center of mass, inertia and Sv in the logarithmic form (dB) were plotted to visualize dissimilarities between the stations (CON, RIV and GLA) and years (2022 and 2023) in terms of their acoustic properties. To assess potential relationships between pelagic biomass and oceanographic conditions among stations and years, the acoustic and CTD datasets were structured in 1 m depth bins and the data merged by depth bin (CON: 5 m – 43 m, GLA: 5 m – 46 m, RIV: 5 m – 37 m in 2022; CON: 5 m – 47 m, GLA: 5 m – 50 m, RIV:

5 m – 34 m in 2023). A correlation matrix was done and a permutational multivariate analysis of variance (PERMANOVA) was conducted with Sv mean in the linear form (m^2/m^3) as the response variable and temperature, turbidity, depth, year and station as explanatory variables. A separate PERMANOVA was conducted with salinity instead of temperature as explanatory variable to avoid multicollinearity between temperature and salinity (Supplementary fig 2). As the top 5 m layer of the acoustic data had to be excluded due to near field noise, the analyses of the environmental data are therefore not including the top layer of the water column. As the CTD water profiles and acoustic transects had slightly different depth ranges, these analyses were performed only for the depth bins where both acoustic and CTD data were available. The “dplyr” and “vegan” packages were used in Rstudio to arrange and export the data as tables and to conduct the NMDS and PERMANOVA analyses. ArcGIS Pro v.3.1 was used to map the locations of the sampling stations.

3. Results

3.1 CTD water column profiles

The bottom depth at the CTD sampling stations was 37.6 m and 34 m at the RIV station, 46.4 m and 50.6 m at the GLA station and 53.7 m and 54.4 m at the CON station in 2022 and 2023, respectively (Table 1, Figure 2). The ranges of temperature (max temperature – min temperature) were highest at the CON station with 10 °C, and lowest at the RIV station with 6.5 °C. Salinity ranges were highest at the GLA station with 18.2 psu, and lowest at the CON station with 3.8 psu. Turbidity ranges were highest at the GLA station with 102.5 ntu and lowest at the CON station with 2.5 ntu. The GLA station showed the highest surface turbidity and lowest surface salinity in both years, indicating a highly stratified surface water layer.

3.2 Pelagic density and vertical distribution

The bottom depths at the study sites during the acoustic mapping surveys ranged from 5 to 56 m (Table 2). The RIV station had a flat and homogenous bottom topography, while the GLA station had an irregular bottom with steep cliffs and the CON station showed a gradual slope (Fig 3).

In 2022, Sv values and standard deviation were two orders of magnitude higher at the CON station than at the other two stations, indicating higher pelagic density and higher variability at this station (Fig 4, Table 2). Several large pelagic aggregations producing a strong backscatter were observed in the echogram and are likely the cause of the high variation in Sv values at the CON station (e.g. Fig 3, right panel). Pelagic density was similar between the glacier and river stations. The glacier station had the deepest center of mass at 24.7 m and highest inertia at 147.2 m^2, which was reflected by a deep and dispersed scattering layer in the echograms from 15 m depth down to the bottom.

In 2023, the GLA and RIV stations displayed higher pelagic density than the previous year, with an increase of one and two orders of magnitude respectively. The RIV and CON stations showed an increase in center of mass which could be linked to several strong scattering aggregations deeper in the water column at both stations (Fig 3). The GLA station showed the lowest backscatter with one order of magnitude lower than the CON and RIV stations, and the highest inertia at 169.7 m^2 reflecting a disperse scattering layer. Despite the interannual differences mentioned above, the CON station consistently reflected the highest pelagic density (Fig 4).

The variability of the logarithmic Sv values between replicates was higher at the CON station, with values ranging from -80 dB to -45 dB (Fig 5). At the GLA and RIV stations, Sv values ranged between -90 dB and -75 dB and between -87 dB and -75 dB respectively.

3.3 Acoustic backscatter and physical oceanography

The correlation matrix showed a high correlation between temperature and salinity (-0.88), and hence these variables were analyzed in separate PERMANOVAs. The PERMANOVA analysis revealed weak but significant effects ($p<0.05$) of temperature turbidity and depth as well as station and year on the variation of pelagic density (Table 3). Of the CTD measurements, turbidity showed the strongest effect with an F value of 27.89, while year showed the strongest effect overall with an F value of 59.74. Temperature had the weakest effect on pelagic density with an F value of 4.87. However, temperature and turbidity only explained ≤ 8% of the variation in pelagic backscatter each, indicating the importance of other drivers. Salinity showed no significant effect on pelagic density with an F value of 1.37 and $p>0.05$ (Table 4).

3.4 BRUV

The BRUV footage revealed an abundance of fish, crabs and large zooplankton at the CON station, in which dense kelp beds could also be observed (Fig 6A). The visibility at the glacier and river stations was low, but the BRUV showed a more homogenous landscape at these stations compared to the CON station, with almost no macroalgae. Three unidentified fish were observed at the glacier station while no organisms were observed at the river station (Table 5).

4. Discussion

4.1 Links between cryosphere changes and pelagic density and distribution

Tidewater glacier fronts are highly productive pelagic environments due to subglacial nutrient circulation, but as these glaciers retreat onto land the upwelling of nutrients disappears. In coastal areas with high influence of land-terminating glaciers either directly in front or due to river runoff from inland glaciers, high sedimentation rates and subsequent low light availability would lead to less productive pelagic ecosystems (Hopwood et al., 2020). Among our three study sites along a gradient of glacier influence, the acoustic data consistently showed higher pelagic density at the CON site with the lowest glacial influence, and the higher standard deviation and wider range of Sv values between the replicates at this site indicate a more productive and dynamic pelagic system at this site than at the GLA and RIV stations with higher glacial influence. Although it is difficult to identify the organisms that compose the scattering structures with a single frequency acoustic system, the large and strong scattering aggregations visible in the echogram at the CON station and large variability of Sv values within grids likely indicate large fish schools. In the absence of data indicating large fish schools, the pelagic density was consistently low which suggests these fish schools and scattering aggregations with high Sv values drive the high pelagic density at the CON station. The echograms and acoustic analyses showed the large strong scattering aggregations to be linked to the bottom, which was consistent with the BRUV footage in which numerous crabs, benthic fish and mysid shrimp appeared next to the bait bag and indicated a rich demersal habitat and high densities of organisms on or near the seafloor.

In contrast, the two glacier influenced stations (RIV and GLA) showed a generally lower pelagic density over the water column, albeit with several small fish schools causing a higher acoustic backscatter at the river station in 2023. While the acoustic data showed fish schools associated to the bottom at the CON station, the scattering aggregations were dispersed across the water column at the river and glacier sites. One explanation for this difference could be due to variation in topography between the study sites. For instance, the steep cliffs at the glacier front at the GLA station likely contribute to a dispersed scattering layer and the observed higher inertia. Conversely, the flatter bottom at the river site may lead to a concentrated scattering layer. Nonetheless, the echograms show distinct patterns in that, when fish schools are present, these aggregations are small and dispersed over the water column at the river and glacier stations, while they are large and associated to the bottom at the CON station as is shown by the higher Sv values and lower inertia. The similarities in pelagic density and distribution between the glacier and river stations, particularly in 2022, may be linked to the parallels in environmental conditions between these two sites, namely the high sediment input from rivers and glaciers, which hinders the settling of benthic primary producers and favors a pelagic-associated ecosystem (Hop et al., 2023). Furthermore, the depth range of the river station was deeper than the depth distribution of macroalgae in Svalbard (Düsedau et al., 2024), but macroalgal growth would not be expected in a river bay with high sediment load. Conversely, the depth ranges at the GLA and CON stations covered shallower ranges (from 5 m and 7 m depth respectively) where macroalgae could be present. Similarly to the river bay, at the glacier front, albeit land-terminating, there is a high sediment input as shown by the high turbidity values and by the BRUV footage and hence the low light regime may hinder macroalgal growth. At the CON station, however, the low glacial input, low turbidity and rocky substrate facilitates macroalgal settlement as seen on the BRUV. These differences in light regime leading to a richer benthic and demersal habitat at the CON station may explain the differences in pelagic density and distribution between the sites.

The ranges in the oceanographic measurements indicated that salinity and turbidity values fluctuate more at the RIV and GLA stations compared to the CON station, particularly in the surface layer, likely due to freshwater and sediment input from the rivers and glacier. Furthermore, the high values of turbidity observed at the glacier station may be linked to sediments being brought by currents from the nearby tidewater glacier plume. The analysis of the relationship between pelagic biomass and oceanographic measurements showed only weak statistically significant effects of temperature, depth and turbidity on the acoustic backscattering strength, and no significant effect of salinity. It should be noted that due to removing the top 5 m of the water column in the acoustic analyses to eliminate near field noise, this shallow layer was also omitted from the CTD data when merging the datasets and therefore is not included in the statistical analyses. As the water column CTD profiles showed, the highest variability in the physical oceanography was in the top layer, likely due to the sediment plumes from the river bay and glacier. Therefore, in the top 5 m environmental conditions may be more important than at deeper depths, as high variations in salinity and temperature can drive the abundance and movement dynamics of fish and zooplankton. Differences in these environmental factors between the stations can drive the patterns of pelagic density and distribution deeper in the water column (e.g. high surface turbidity at the glacier front reduces light availability and may alter the vertical distribution of fish and zooplankton). However, as temperature, depth, salinity and turbidity explained little of the variation, other factors must thus have a major role to drive ecosystem dynamics. As seen on the BRUV footage, there was a rich benthic and demersal ecosystem at the CON station, characterized by dense kelp beds, at least in the shallow areas that are within the depth distribution of kelp in Svalbard Conversely, little macroalgal coverage was observed at the river and glacier stations, likely due to the high sediment input, low light availability and soft bottom substrate. The BRUV was deployed in 2021 and therefore not concurrent with the acoustic study, and hence there are limitations in comparing these data, but the underwater footage provides a snapshot of the benthic habitat and substrate type, which is likely an important driver for pelagic density at the deeper parts of the stations. The high sedimentation at the river and glacier sites was visible in the BRUV footage, while there was more light availability and hard substrate at the site with less terrestrial runoff.

In shallow areas with hard bottom, low sedimentation input and little mechanical disturbance, macroalgal growth can be stimulated and lead to a high associated biomass of organisms that feed on the algae or use them as shelter or nursery grounds (James & Whitfield, 2023; Lippert et al., 2001; Teagle et al., 2017). Glacier and sea-ice retreat open up new areas where marine organisms can settle, and previous studies have shown that macroalgae are expanding northward (Assis et al., 2022; Krause-Jensen & Duarte, 2014) and settling at retreating glacier fronts (Deregibus et al., 2023; Gonzalez Triginer et al., 2024). In shallow coastal areas, these demersal habitats can also benefit pelagic fish and zooplankton, which may explain why both the demersal habitat richness and pelagic density were consistently higher at the CON site. The effects of the expansion of these habitats in the Arctic on fjord ecosystem dynamics are complex, and conducting similar studies in other areas would aid in understanding their potential in mitigating the loss of pelagic productivity due to glacial retreat. Our results are consistent with the literature in showing that areas influenced by land-terminating glaciers and rivers may be linked to lower density of fish and zooplankton compared to areas without the influence of terrestrial runoff (Hopwood et al., 2020). In our study, the site with the highest recorded pelagic density had the lowest influence from rivers and glaciers, which potentially allowed for settlement and growth of macroalgae. It has been suggested that an enhanced demersal habitat expanding into areas previously covered by tidewater glaciers might be beneficial to both benthic and pelagic organisms, at least in shallow ecosystems. A recent study in inner Billefjorden recorded macroalgal settlement in areas that were covered by the glacier until very recently, while there was virtually no macroalgal coverage at the river bays (Gonzalez Triginer et al., 2024). However, there is limited data on the potential of macroalgal expansion to offset the loss of productivity driven by subglacial upwelling in high Arctic fjords, and it is likely closely linked to fjord topography and land runoff in coastal fjord areas, and hence highly vary between fjord systems. More research is needed to further study the expansion of rich demersal habitats following glacial retreat and their role in ecosystem dynamics and fjord productivity in the Arctic.

4.2 The potential of autonomous hydroacoustic surveys in coastal areas

The acoustic properties of the water column in shallow coastal areas can be highly dynamic and complex, and therefore both echogram visualization and data analyses need to be taken into consideration when interpreting the results. Moreover, complementing the acoustic data with underwater video and oceanographic measurements further aids in understanding the complexity of a spatial comparison of pelagic distribution. As a measure of the average backscatter depth in the water column, the center of mass metric is sensitive to being skewed by outliers in the data such as fish aggregations. Inertia is a measure of dispersion or spread of scatterers, and it considers both the squared distances from the center of mass and their Sv values (Urmy et al., 2012). Therefore, inertia is less sensitive to outliers and can lead to a representative measure of pelagic dispersion, and a combination of center of mass and inertia are a more robust measure of the location and dispersion of the pelagic scattering layer.

The efficiency of hydroacoustics to map and assess pelagic biomass in the Arctic has been shown in multiple studies (e.g. Benoit et al., 2008; Geoffroy et al., 2019; Kaartvedt et al., 2009), but validation of acoustic data is still critical to identifying species and functional groups. Validation of such data is often done by trawl surveys (Geoffroy et al., 2019), but when working in shallow littoral areas it is often not possible to trawl, and alternative validation methods are very limited and often biased, especially in muddy and shallow glacier front areas.

Acoustic surveys have been done in the high Arctic in the past to map macroalgae coverage (Kruss et al., 2017; Wiktor et al., 2022), and such methodology can be adapted to study the pelagic environment in these areas. The inaccessibility of glacier fronts and remote areas in the high Arctic makes it challenging to use traditional methods for marine sampling in coastal areas, and autonomous hydroacoustic and remote sensing techniques can be used to safely and efficiently study these sites, which are undergoing large changes due to climate shifts. The use of such novel methodology allowed for sampling very close to the glacier front, which would not be possible from a ship. This allowed to gain new insight on glacier fronts, which, as boundaries between the cryosphere and the marine ecosystem, are key areas to understanding the effects of climate change on marine biological processes. As rich benthic habitats such as kelp forests expand following glacier retreat, littoral fjord areas in the high Arctic may be more resilient to loss of biomass and biodiversity than previously thought.

Acknowledgements

We would like to thank Kathy Dunlop and the Institute of Marine Research for the loan of the BRUV and for helping with the setup. We also thank the technical staff at the University Centre in Svalbard for their support during long hours of fieldwork. We would like to thank the reviewers for their valuable input which helped to improve our manuscript.

Competing interests

The authors declare there are no competing interests.

Funding

This study was financed through the FACE-IT project which has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 869154. MG acknowledges funding from the Canadian Natural Sciences and Engineering Research Council (NSERC) Discovery Grant program, and RCN-funded projects Deep Impact (#300333) and Opkrop (#343352).

Data availability

The CTD profile datasets are publicly available at https://doi.org/10.5281/zenodo.13323435. The acoustic data generated and analyzed during this study fall under confidentiality regulations of the Norwegian Mapping Authority.

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Tables

Table 1. Bottom depth (m) and descriptive statistics of the oceanographic measurements per station and year. Temperature in degrees Celsius, salinity in practical salinity units and turbidity in nephelometric turbidity units (ntu).

Station	Year	Bottom depth	Temperature range	Salinity range	Turbidity range
RIV	2022	37.6	7.1	14.5	13.1
RIV	2023	34	6.5	9.2	8.4
GLA	2022	46.4	7.6	18.2	102.5
GLA	2023	50.6	9.5	11.7	22.7
CON	2022	53.7	10	8.1	2.5
CON	2023	54.4	9.8	3.8	2.8

Table 2. Results from the integration of the acoustic data showing Sv mean, center of mass, inertia and standard deviation for the means of all the replicates.

Station	Year	Bottom depth range (m)	Sv mean (m^2/m^3)	Center of mass (m)	Inertia (m^2)	Standard deviation
RIV	2022	24 - 42	5.3e-09	13.2	66.4	1.7e-07

RIV	2023	24 - 43	1.6e-07	24.8	102.6	8.5e-06
GLA	2022	10 - 49	7.6e-09	24.7	147.2	1.5e-07
GLA	2023	5 - 56	3.3e-08	22.4	169.7	1.2e-06
CON	2022	7 - 45	8.9e-07	17.1	44.9	2.7e-05
CON	2023	13 - 50	2.2e-07	31.3	97.3	6.3e-06

Table 3. PERMANOVA with 999 permutations of Sv mean as the response variable and temperature, turbidity, depth bin, year and station as explanatory variables.

	Df	SumOfSqs	R2	F	Pr(>F)
Temperature	1	0.86	0.01	4.87	0.005
Turbidity	1	4.93	0.08	27.89	0.001
Year	1	10.57	0.17	59.74	0.001
Station	2	6.18	0.10	17.48	0.001
DepthBin	1	1.27	0.02	7.16	0.001
Residual	226	39.97	0.63	NA	NA
Total	232	63.79	1.00	NA	NA

Table 4. PERMANOVA with 999 permutations of Sv mean as the response variable and salinity, turbidity, depth bin, year and station as explanatory variables.

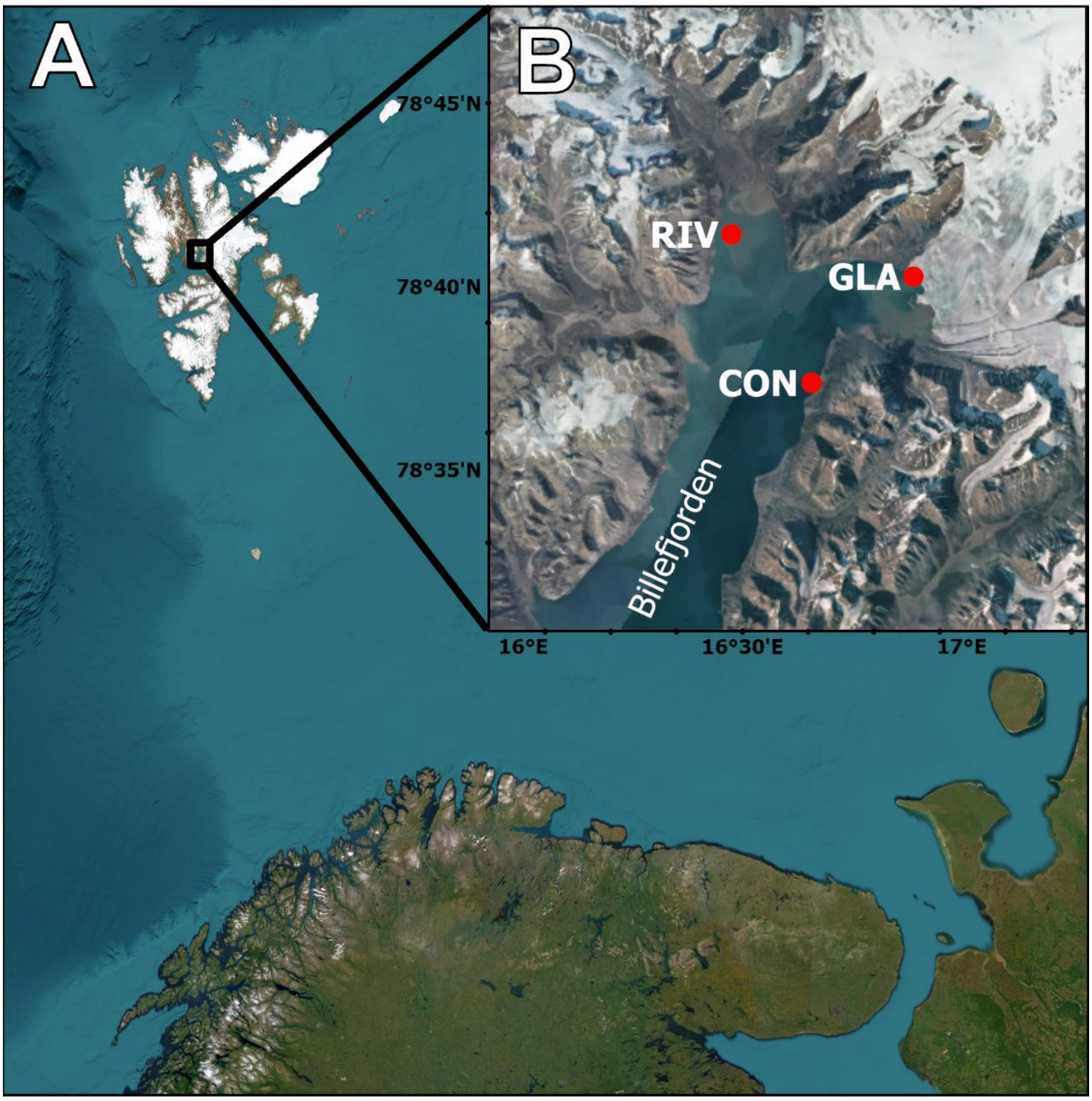
	Df	SumOfSqs	R2	F	Pr(>F)
Salinity	1	0.25	0.00	1.40	0.236
Turbidity	1	4.91	0.08	27.55	0.001
Year	1	11.05	0.17	62.05	0.001
Station	2	6.34	0.10	17.79	0.001

DepthBin	1	0.97	0.02	5.47	0.003
Residual	226	40.26	0.63	NA	NA
Total	232	63.79	1.00	NA	NA

Table 5. Summary of the BRUV deployment data and maximum observed number of a taxa in a single frame (MaxN). There were 60 observations per hour (1 minute each) at every station, and all deployments were done at 10 m depth.

Station	Latitude (°N)	Longitude (°E)	Fish MaxN	Zooplankton MaxN
CON	78°37.063	16°40.704	6	100+
GLA	78°40.062	16°55.563	3	0
RIV	78°41.054	16°27.768	0	0

Figures

542 

543 Figure 1. A) Study area in Svalbard. B) Satellite image of Billefjorden with the study stations (site with

544 a recently land-terminating glacier – GLA, river bay – RIV and site with low glacial input - CON. Map

545 source: Earthstar Geographics and Norwegian Polar Institute.

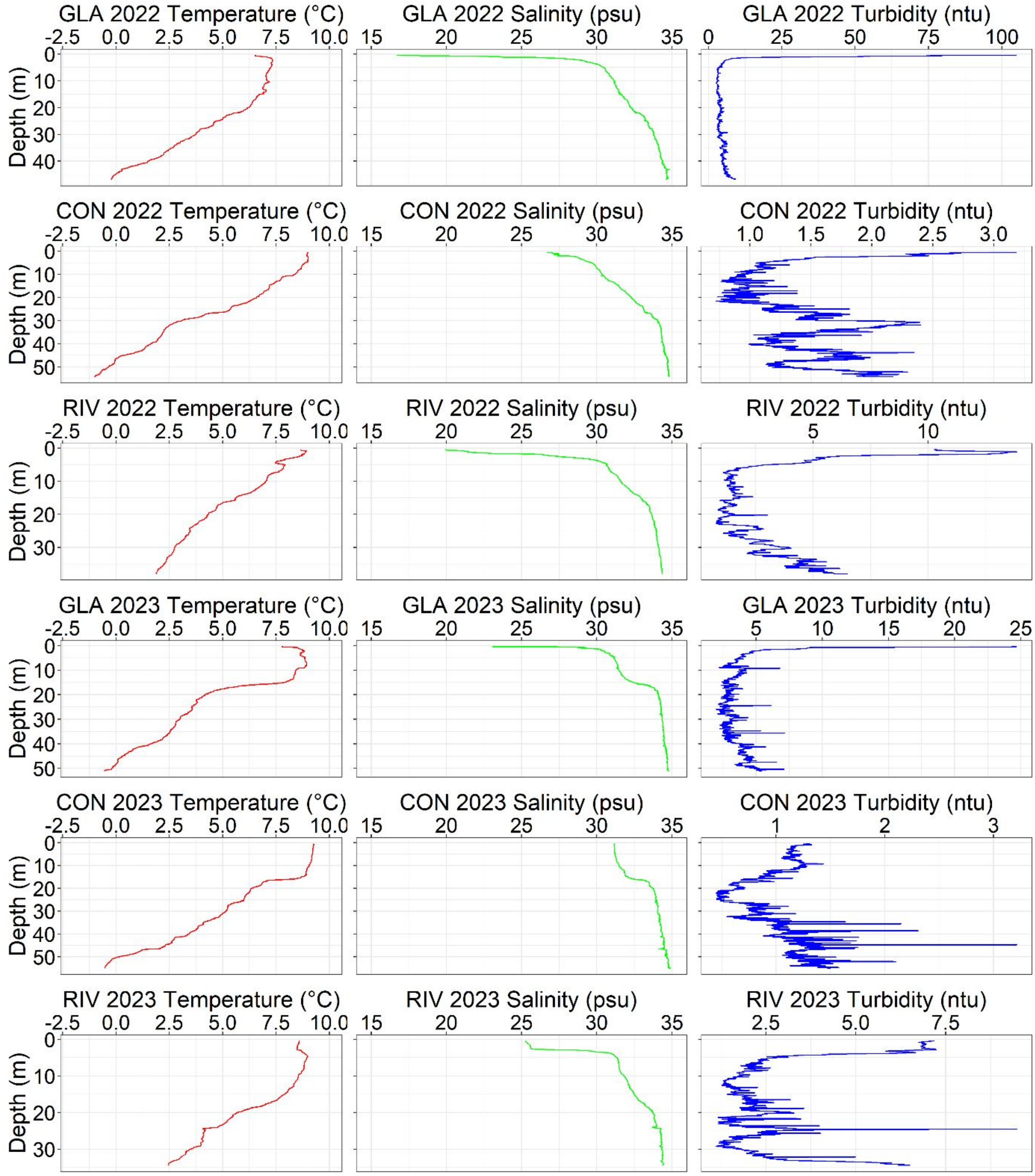
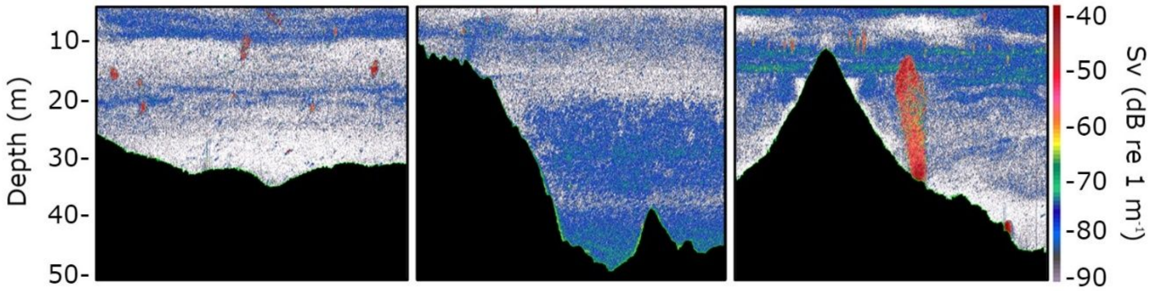
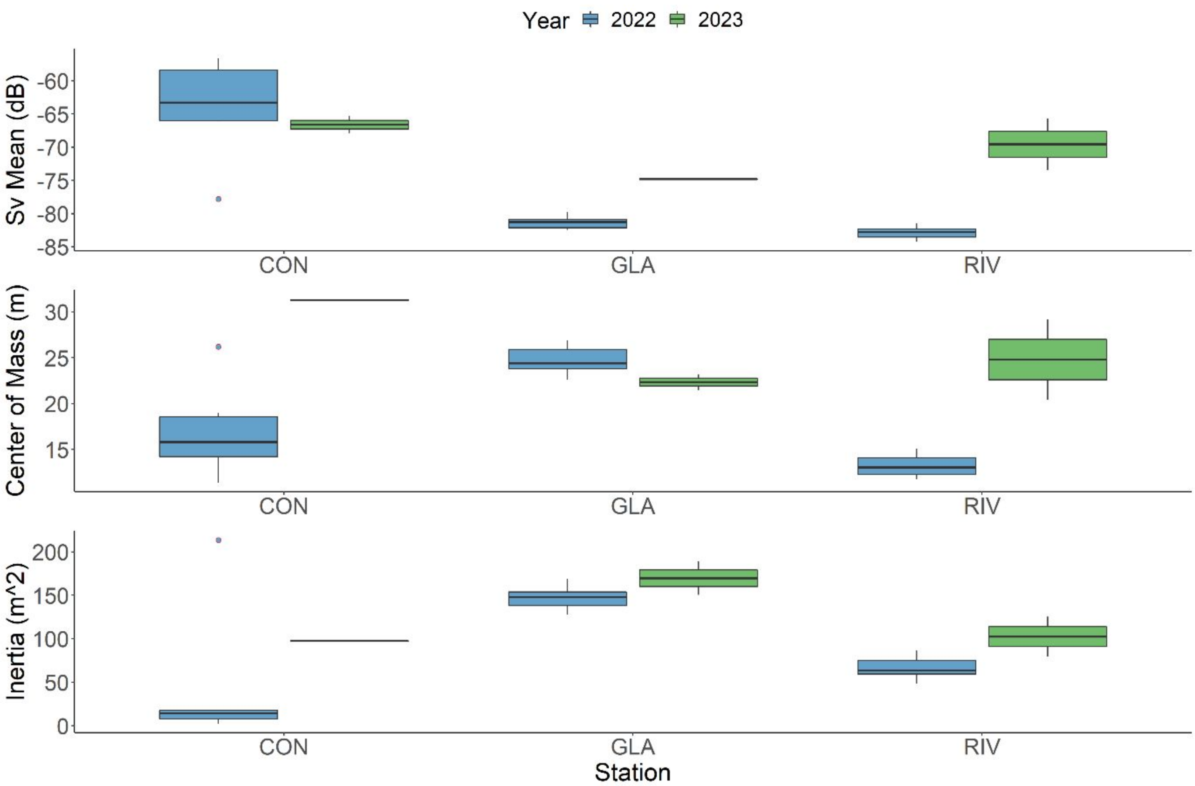


Figure 2. CTD water column profiles for the glacier (GLA), CON and river station (RIV) in 2022 and 2023 with measurements of temperature, salinity and turbidity.



549

550 Figure 3. Echogram snapshots of the RIV (left), GLA (middle) and CON (right) stations from 2023.



551

552 Figure 4. Differences among stations in acoustic parameters (logarithmic Sv mean, center of mass and

553 inertia). Mean values for Sv, center of mass and inertia were extracted for each transect (6 replicates

554 in 2022 and 2 replicates in 2023) and are presented by station and year. The box represents the

555 interquartile range (IQR) and the line within indicates the median. The whiskers extend to the most

556 extreme data points not considered outliers, which are represented by individual dots beyond the

557 whiskers.

558

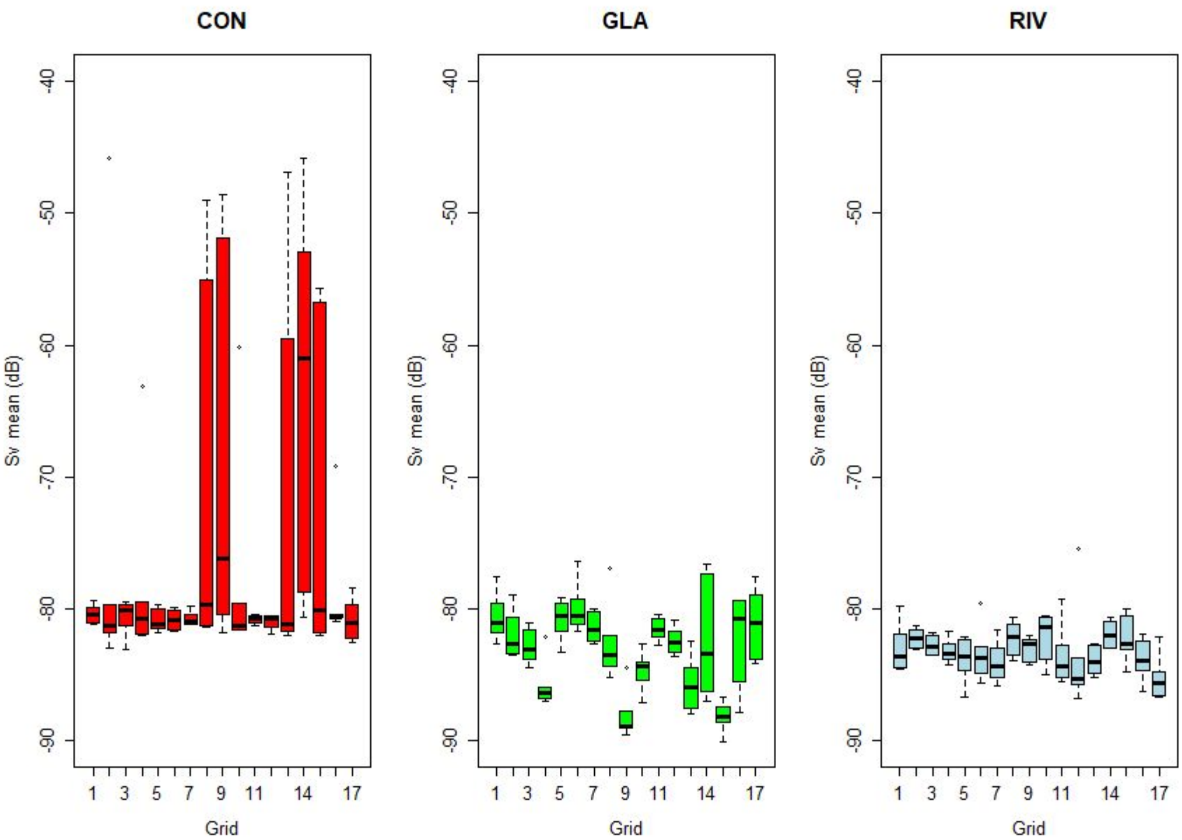


Figure 5. Boxplots showing the ranges of Sv (dB) mean for each grid at the CON, GLA and RIV stations in 2022.

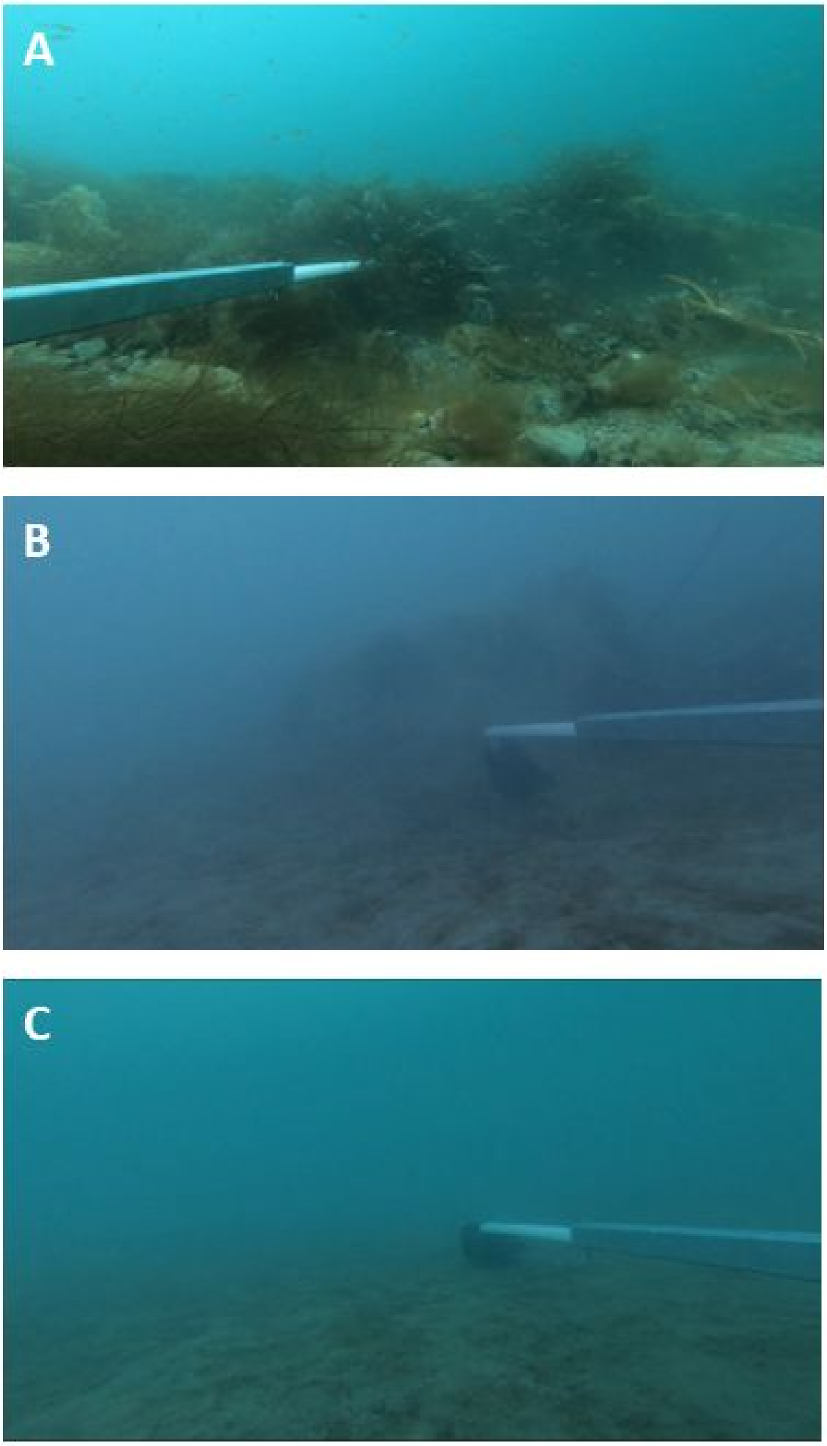


Figure 6. Snapshots from the BRUV deployment at (A) the CON station, (B) the GLA station and (C) the RIV station.