Evaluating the effects of climate change on Arctic char

- including impacts of brown trout competition

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Swedish University of Agricultural Sciences, SLU
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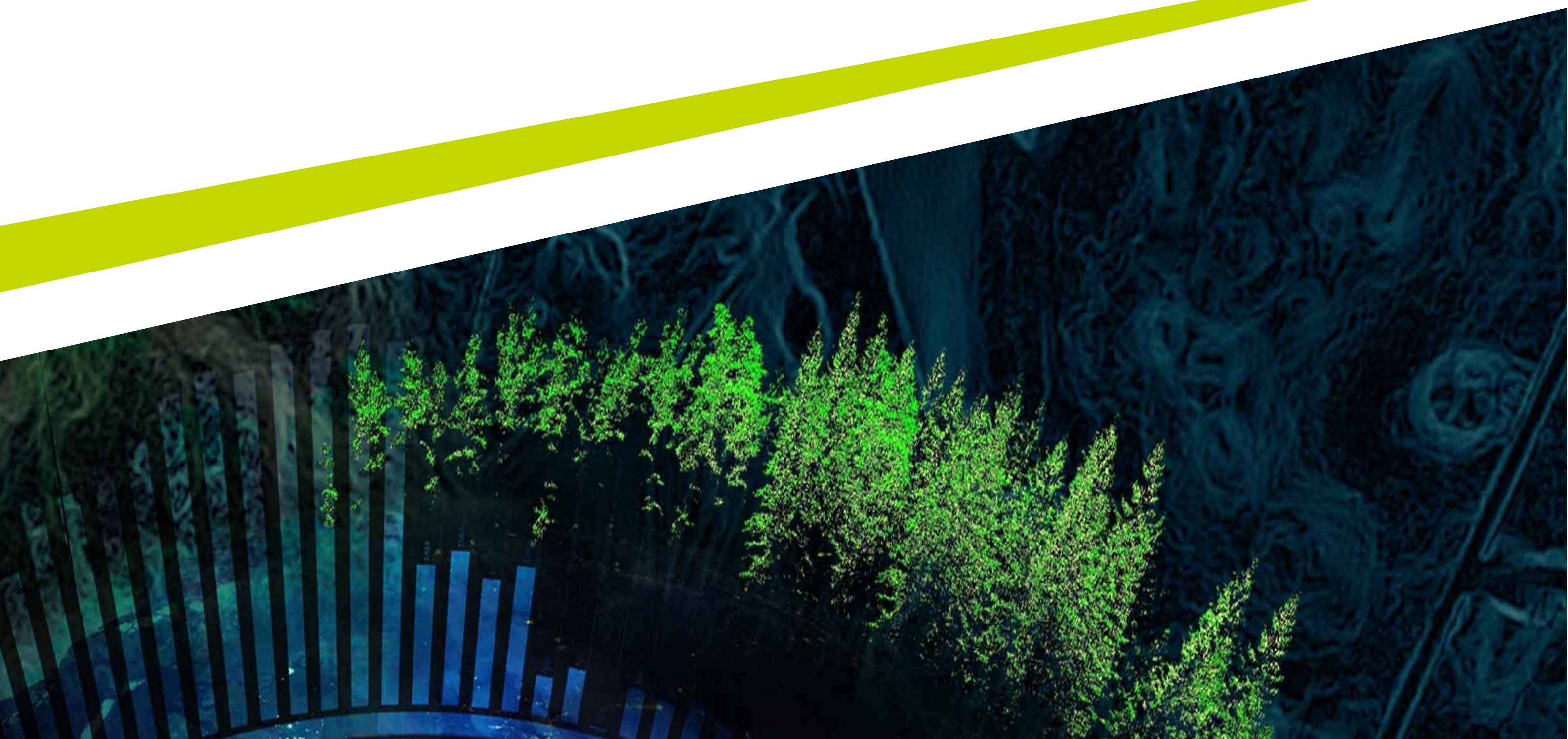

Evaluating the effects of climate change on Arctic char - including impacts of brown trout competition

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Abstract

Climate change is predicted to increase the average global temperature with 1.5 °C between 2030 and 2052. The areas that are most vulnerable for climate change are the arctic regions. Arctic char (*Salvelinus alpinus*) is a cold-water salmonid species with the most northern distribution of all freshwater fish species. The distribution area of Arctic char in Sweden is predicted to decrease with 73 % by 2100, both as a result of warmer climate and changed species interactions. Here, I have studied how climate change will affect the habitat- and food choice as well as the growth of Arctic char, both in waters where brown trout (*Salmo trutta)* are absent (Abiskojaure), and in waters where they are present (Stor-Björsjön). By analysing available catch data from both lakes, habitat selection of Arctic char and brown trout could be studied. Food choice was studied by examining stomach content, and growth by measuring annual growth rings on otoliths. My results show that the habitat selection of Arctic char in Abiskojaure was only dependent on the size of the fish, where fish in the small and large size ranges (< 101 mm, 301 – 400 mm and > 400 mm) were found in shallower water compared to fish in the intermediate size ranges (101 – 200 mm and 201 – 300 mm). In Stor-Björsjön the habitat selection for Arctic char was dependent on both size of fish and surface temperature. In Stor-Björsjön, Arctic char in the small and large size ranges (< 101 mm and > 300 mm) were found at a wider range of depths compared to Arctic char in the intermediate size ranges (101 – 200 mm and 201 – 300 mm), which were found in a more limited depth span. The Arctic char tended to stay deeper as surface temperatures increased, and where brown trout was present. Arctic char's diet in Abiskojaure mainly consisted of crustaceans, but in Stor-Björsjön, pelagic zooplankton were the main food source. Differences in annual growth could be seen between younger and older Arctic char. In Abiskojaure warm or cold years did not affect the annual growth over age differently. In Stor-Björsjön however, younger Arctic char benefitted in growth from the warmer water, in contrast to older fish that had lower growth in warm waters compared to cold. In short, my results indicate that climate change, and the consequences of it, are likely to have a negative effect on the Arctic char population in Sweden. In Stor-Björsjön, where water temperatures sometimes exceed the optimal temperature range for the Arctic char, they utilize deeper water with higher surface temperatures, showing they prefer colder water. The growth of larger Arctic char is also lower in warmer compared to colder years in Stor-Björsjön, further indicating the preference of colder water. In Stor-Björsjön, where Arctic char and brown trout co-exist, the two species inhabit different parts of the lake. The brown trout shallower areas since they are stronger competitors for littoral resources during the ice-free period. It is unclear how severely the Arctic char will be affected of climate change in the future and further studies are required to understand the situation better and to take measures to preserve the species to as large extent as possible.

Keywords: Arctic char, brown trout, climate change, diet, habitat use, temperature

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1. Introduction

Arctic char (*Salvelinus alpinus*) is a common cold-water salmonid species in northern Sweden (Hein et al. 2012). Arctic char constitutes the most northern populations of all freshwater and anadromous fish species, with populations on Iceland and Greenland being found at the highest latitude (Klemetsen et al. 2003). The Arctic char in Sweden is only found in freshwater, mainly in the alpine region in streams and lakes, but sparse populations occur all across the country, except for the most southern parts (Hein et al. 2012; Artdatabanken 2022). Since Arctic char is adapted to cold water environments, it is often the only fish species found in alpine lakes (Hesthagen et al. 1997). In lakes below the alpine region the Arctic char often lives in sympatry with brown trout (*Salmo trutta*) (Forseth et al. 2003). Arctic char is a generalist when it comes to diet and habitat choice, but it is affected by the competitive situation within the lake (Klemetsen et al. 2003). When brown trout are absent, and there is less intra-specific competition for resources, Arctic char prefers to inhabit the littoral zone (Klemetsen et al. 2003; Urban et al. 2011). When Arctic char lives in sympatry with brown trout, the competitive situation will likely have a negative effect on Arctic char. Brown trout is a stronger competitor for littoral resources during the ice-free period, which will force Arctic char to utilize the pelagic zone as habitat (Klemetsen et al. 2003; Langeland et al. 1991; Urban et al. 2011). This then in turn also narrows the food choice for Arctic char, that will mainly feed on pelagic zooplankton or insects on the surface (Gregersen et al 2006; Skoglund et al. 2013). Should the winters be shorter, the competition might be too severe for the Arctic char to co-exist with the brown trout. Exceptions are large lakes where the summer habitat, i.e. the pelagic, is large enough to avoid competition from brown trout (Urban et al. 2011).

Global warming has led to an increased average temperature of 1 °C in 2017 compared to pre-industrial levels, and it is likely to increase to 1.5 °C between 2030 and 2052 (IPCC 2022). Although many areas already experience local temperatures higher than the global average increase. The arctic regions are the areas that are likely to be most affected by global warming, both considering increased temperatures, but also changed seasonal patterns (Bintanja & Van der Linden 2013).

During the last decades the lakes in northern Sweden have been heavily impacted by climate change, leading to increased temperatures and changed seasonal pattern (Bintanja & Van der Linden 2013). With the Arctic char having the most northern distribution of all freshwater fish species, it will be most vulnerable to these changes. The opportunity for migrating further north when water temperatures increase is limited. Therefore the only option for seeking cooler water is to inhabit deeper parts of the lake (Hein et al. 2012; Reist et al. 2006). Changes in temperature will likely affect the behaviour, habitat and food choices of Arctic char, and also its interaction with brown trout. When water temperatures increase, the metabolism and energy requirements of the Arctic char will increase (Hein et al. 2012; Reist et al. 2006). If resources are available this will lead to higher consumption rates and higher growth rates in Arctic char. The optimum temperature for Arctic char is between 14.4 °C and 17.2 °C, given endless resources. Under natural circumstances however, this temperature optimum is likely much lower (Hein et al. 2012). Up until the optimal temperature the metabolism increases slowly (Budy & Luecke 2014). With many of the lakes in the alpine region never reaching these high temperatures for longer periods of time during the summer, the low temperature may be the limiting consumption factor in some lakes, and not food abundance (Budy & Luecke 2014). In the study by Budy & Luecke (2014) the specific growth rate was the highest among the smaller Arctic char, and lowest for the larger Arctic char, but all fish were positively affected by higher temperatures (Budy & Luecke 2014). However, warmer water is not only positively affecting the Arctic char. The consumption and growth rates slowly increase with higher temperatures up until a certain point where they rapidly decrease. This is the point when the Arctic char population will be negatively affected and risk dying (Budy & Luecke 2014). It is predicted that by 2100 the distribution area of the Arctic char population in Sweden will decrease with 73 %, both as a result of climate change and predicted pike invasion and increased predator efficiency with the higher temperatures (Hein et al. 2012).

2. Aim and Objectives

The aim of this study is to investigate how increasing temperatures will affect Arctic char in Swedish mountain lakes. This will be done by comparing the growth and habitat use of Arctic char in warmer and colder years, which can give indications of what will happen in the future. Furthermore, this will be performed in one lake with and one lake without brown trout present to determine how brown trout influences Arctic char behaviour. The stomachs content of Arctic char will be examined to determine what they feed on and how this is influenced by the presence of brown trout. The lakes that will be studied are Abiskojaure and Stor-Björsjön which are situated in the northern parts of Sweden.

Hypotheses

- Arctic char will change their habitat use and utilize deeper water when water temperatures are high
- In lakes with brown trout, Arctic char will have modified their habitat use towards deeper water and their diet towards smaller invertebrates and zooplankton, due to the competition from brown trout
- Small Arctic char will benefit from warmer water and grow faster, while larger Arctic char will be negatively affected

3. Material and Methods

3.1 Lakes studied

Abiskojaure is situated in the county of Norrbotten, in the municipality of Kiruna (Figure 1). It has an area of 282 hectares and a maximum depth of 35 m. The only fish species present in Abiskojaure is Arctic char (SLU 2009a).

Stor-Björsjön is the other lake studied and is situated in the county of Jämtland, in the municipality of Åre (Figure 1). Stor-Björsjön has an area of 35 ha and a maximum depth of 15 m. Both Arctic char and brown trout are found in the lake (SLU 2009b).

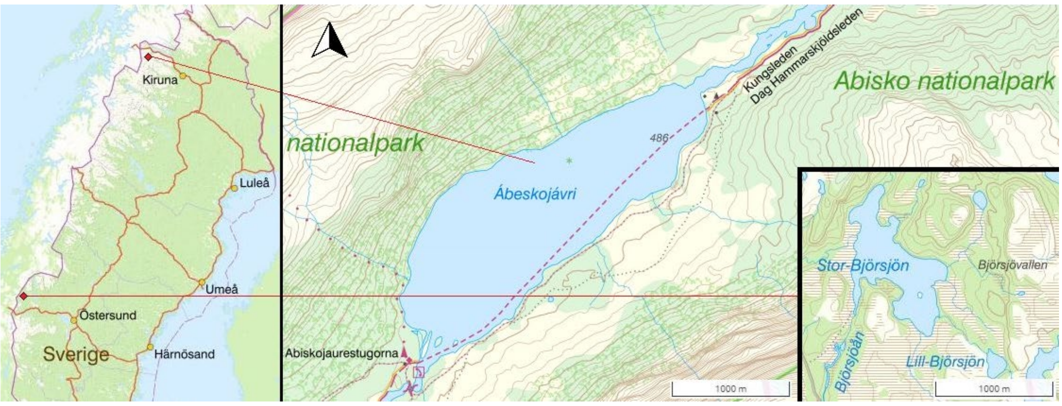

Figure 1. Map of the studied lakes Abiskojaure and Stor-Björsjön

3.2 Field work

3.2.1 Gillnet fishing

In this study all the fish sampled have been caught by gillnet fishing, performed by SLU Aqua as a part of their ongoing environmental monitoring (SLU 2022). Gillnet fishing is a widely used method for scientific studies where fish populations are studied over time (Appelberg et al. 1995). In this study the majority of nets used have been sinking nets. The mesh size varied from nets with only one mesh size, to nets with multi-sized mesh. The nets with multi-sized mesh are so called NORDIC gillnets and currently used as a standard for gillnet fishing. The NORDIC gillnets have mesh sizes 5, 6.25, 8, 10, 12.5, 15.5, 19.5, 24, 29, 35, 43 and 55 mm where each section is 2.5 m long, and the net height is 1.5 m (Appelberg et al. 1995). When the nets are placed, the depth of the water is checked with a sonar, at the beginning and end of each net. In addition to the standardized net fishing, additional fish samples from Abiskojaure were collected by the Swedish Museum of Natural History and kept in freezers.

3.2.2 Fish analysis

For each fish caught during the standardized gillnet fishing, the net number in which the fish was caught was noted. Also all fish that were caught were measured, weighed, and determined for sex and maturity level status. For a number of fish otoliths were removed and determined before being frozen for further analysis analysed at in the lab (SLU Aqua).

Stomach samples from fish caught during standardized fishing in Stor-Björsjön in year 2018 were preserved in alcohol for later analysis. While fish stomach samples from Abiskojaure (year 2020 and 2021) and Stor-Björsjön (year 2020 and 2021) were retrieved from the frozen samples kept at the Swedish Museum of Natural History.

3.3 Laboratory work

3.3.1 Stomach content analysis

For the stomach content analysis, the stomach content was placed on a petri dish together with some ethanol. It was looked at under a microscope and each food item was identified to the appropriate taxonomic level. For each taxonomic group/species, the number of individuals were counted and measured. If there were many individuals of the same taxonomic group/species the number was estimated by sub-dividing the sample, counting the individuals within the sub-sample, and then rescaling it to the full sample size. For each taxonomic group/species a total of 10 individuals were measured and the mean value of these 10 was set as the size for the remaining individuals, in case there were more. In case there was an empty stomach, it would be noted as a 0. The different taxonomic groups/species were later assigned into 9 different groups: Bythotrephes, Eurycercus, Pelagic zooplankton, Diptera, Crustaceans, Mollusks, Predator sensitive macroinvertebrates (PSM), Terrestrial and Other (Table 1). In this study, stomach content from 24 Arctic char from 2020 and 24 Arctic char from 2021 from Abiskojaure was examined. In Stor-Björsjön, stomach content from 57 Arctic char and 25 brown trout from 2018, 10 Arctic char from 2020 and 12 Arctic char from 2021 was examined. The lengths and count from each taxonomic group/species was used to determine the biomass of the different groups in each fish stomach.

Table 1. Taxonomic groups found in the stomachs divided into groups, and what areas of the lakes these are most commonly found

Groups	**Invertebrate species/genus/group**	**Benthic zone**	**Surface zone**	**Pelagic zone**
Bythotrephes	*Bythotrephes*			X
Eurycercus	*Eurycercus*	X		
Pelagic zooplankton	*Bosmina* *Daphnia* *Copepoda*			X
Diptera	*Chironomidae* *Ceratopogonidae*	X		
Crustaceans	*Gammarus pulex* *Lepidurus* *Mysis*	X		
Mollusks	*Gastropoda* *Bivalvia*	X		
PSM	*Tricoptera* *Ephemeroptera* *Coleoptera* *Megaloptera*	X		
Terrestrial	*Terrestrial insects*		X	
Other	*Ants* *Nematodes* *Fish* *Fish-eggs* *Worms*	X		

3.3.2 Otolith analysis

Sagittal otoliths from Arctic char can be used to determine the age and the growth of the fish. An otolith has annual growth rings, developed due to the different growth of the otolith during the season. By measuring the distance between the annual growth rings, and accounting for the total length of the fish, annual growth can be calculated (Finstad 2003). To do this the otoliths from one fish was placed in a petri dish with some contrast liquid. This was placed under a microscope with a camera attached to it. Pictures were taken of both otoliths, of the convex side of the otolith, where the annual growth rings are the clearest. The pictures were analysed in ImageJ with the plugin ObjectJ. The distance from the centre of the otolith to the middle of each year ring, all the way to the outer edge was measured. The distance from the last growth ring to the outer edge wasn't a full year of growth and was excluded from the analysis. The measurements were done in at least four different directions on every otolith (Figure 2). In this study, otoliths from 5 Arctic char from 2012, 6 Arctic char from 2013 and 15 Arctic char each from 2014, 2015 and 2019 from Abiskojaure were examined. In Stor-Björsjön, otoliths from 15 Arctic char from 2014, 12 Arctic char from 2015 and 15 Arctic char from 2019 were examined. All the fish were already age determined, and the age classes were 1+, 2+, 3+, 4+ or 5+.

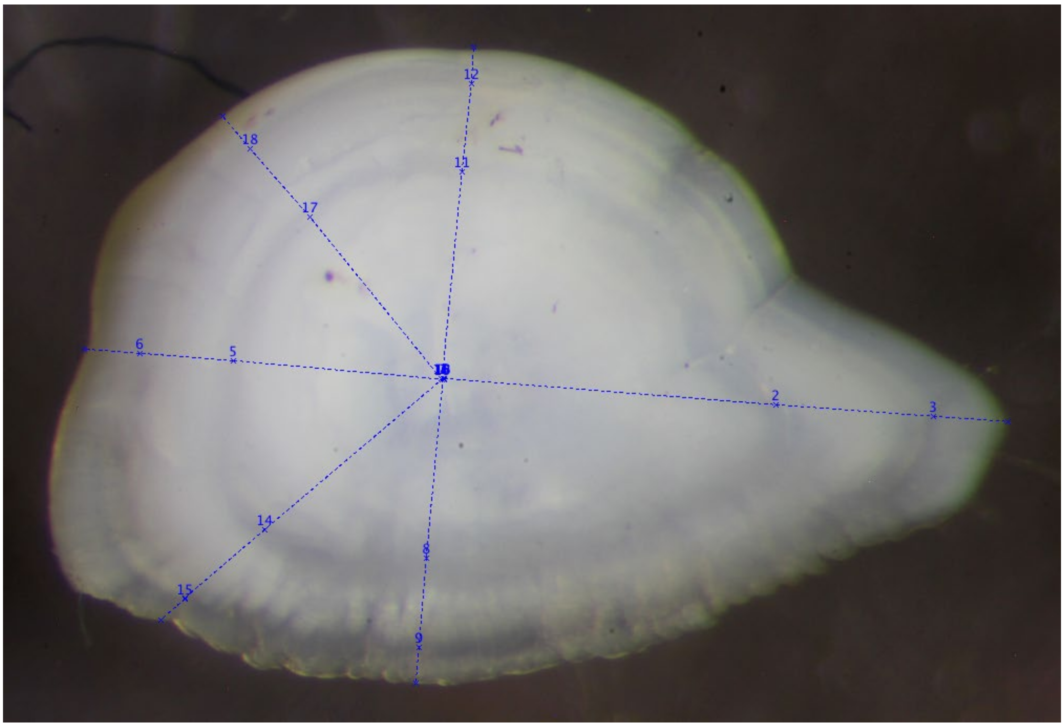

Figure 2. Example of measurements of an otolith for a 2+ Arctic char

3.4 Data analysis

Data analyses were done in RStudio (version 4.1.1) with the packages tidyverse, ggplot2, vegan and car. All significance levels for the statistical analyses were set to $p = 0.05$.

3.4.1 Habitat selection

Data on the depth of capture for all caught fish from Abiskojaure from 1994 to 2021 and Stor-Björsjön from 2002 to 2021 were obtained. The fish were sorted according to fish length categories. In Abiskojaure a total of 4040 Arctic char have been caught, and were sorted into five size groups: Size group 1 (< 101 mm; $n_{\text{Arctic char}} = 245$), size group 2 (101 – 200 mm; $n_{\text{Arctic char}} = 1586$), size group 3 (201 – 300 mm; $n_{\text{Arctic char}} = 1403$), size group 4 (301 – 400 mm; $n_{\text{Arctic char}} = 649$) and size group 5 (> 400 mm; $n_{\text{Arctic char}} = 157$) (Appendix 1). In Stor-Björsjön a total of 1230 Arctic char and 625 brown trout have been caught and were sorted into four size groups. Size group 1 (< 101 mm; $n_{\text{Arctic char}} = 73$, $n_{\text{brown trout}} = 9$), size group 2 (101 – 200 mm; $n_{\text{Arctic char}} = 659$, $n_{\text{brown trout}} = 291$), size group 3 (201 – 300 mm; $n_{\text{Arctic char}} = 483$, $n_{\text{brown trout}} = 257$) and size group 4 (> 300 mm; $n_{\text{Arctic char}} = 15$, $n_{\text{brown trout}} = 68$) (Appendix 1). The reason for having four size groups in Stor-Björsjön was that only two fish were larger than 400 mm. Mean catch depth and temperature were calculated for each size group and year (and fish species in Stor-Björsjön). An analysis of variance (ANOVA) was performed to investigate if and how the average catch depth and average catch temperature differed between Arctic char in the two lakes. The factors tested for average catch depth of Arctic char in Abiskojaure were size groups, surface temperature and the interaction between these. For the average catch depth of Arctic char in Stor-Björsjön, fish species and the interaction with both size groups and surface temperature were also factors tested. The factor tested for average catch temperature of Arctic char in Abiskojaure was size groups. For the average catch temperature of Arctic char in Stor-Björsjön, fish species and the interaction with size groups were also factors tested. If a significant effect could be seen, a post-hoc test, in this case Tukey HSD, was performed.

3.4.2 Stomach content

The stomach content was analysed to determine if there was any difference in food choice between Arctic char in Abiskojaure and Stor-Björsjön, and between the Arctic char and brown trout in Stor-Björsjön. The fish were sorted according to the same size groups as described above. Permutational multivariate analysis of variance (PERMANOVA, *vegan package, function adonis2*) tests were performed to investigate if diet composition differed between both the Arctic char in Abiskojaure and Stor-Björsjön, and if diet composition differed between the Arctic char and brown trout in Stor-Björsjön. The factor tested between the two populations of Arctic char was the interaction between lake and size group. The factor tested between Arctic char and brown trout in Stor-Björsjön was the interaction between species and size group. To visualize the diet results a non-metric multidimensional scaling (NMDS) was used.

3.4.3 Growth determination

The otolith data was analysed to determine the annual growth of each individual fish. From the measurements done in different directions on the same otolith, mean distance between the centre of the otolith and the annual growth rings was calculated. This was done for every otolith. Using these values and formula (3) from Finstad 2003 (below) the total length for each fish and year could be back calculated. The mean total length from the calculations of the two otoliths from the same fish was set as the total length for the fish each year. From the total length each year, the annual growth increment could be calculated by subtracting the total length one year with the total length the previous year.

Formula (3): $L_t = [O_t O_T^{-1} (\beta_0 + \beta_1 L_T + \beta_2 T + \beta_3 L_T T) - \beta_0 - \beta_2 t](\beta_1 + \beta_3 t)^{-1}$

L_t is the back calculated total length for the fish at age t. T is the age at capture. O_T is the otolith radius at the age of capture and O_t is the otolith radius at age t. β_0, β_1, β_2 and β_3 are constant coefficients (Finstad 2003).

The classification of warm and cold years was based of surface temperature of the water (Appendix 4). In Abiskojaure, 2012 and 2015 were classified as cold and 2014 and 2018 were classified as warm years. In Stor-Björsjön, 2013, 2015 and 2017 were classified as cold and 2014 and 2018 were classified as warm years.

For each lake an analysis of covariance (ANCOVA) was performed to test whether the warm or cold years had an effect on the mean annual growth of Arctic char of different ages. In case a significant interaction effect could be seen, a linear regression model (with age as the explanatory variable) was fitted for warm and cold years separately, and if not for all years together.

4. Results

4.1 Habitat selection

In Abiskojaure, depth at catch was significantly affected by size group, but not by the surface temperature (Table 2). Neither was the interaction between the two significant (Table 2). The Tukey HSD test showed there was a significant difference in depth choice between all the size groups except for group 1 and 5, group 4 and 5 and group 2 and 3 (Appendix 2). Arctic char in size groups 1, 4 and 5 live shallower compared to the Arctic char in size group 2 and 3 (Figure 3). Temperature at catch was also significantly affected by size group (Table 2). The Tukey HSD test showed there was significant difference in temperature choice between all the size groups except for group 1 and 5 and group 4 and 5 (Appendix 2). The Arctic char in size group 1, 4 and 5 tend to live in warmer water compared to the Arctic char in size groups 2 and 3 (Figure 5).

In Stor-Björsjön, depth at catch was significantly affected by size group, surface temperature and fish species identity (Table 2). The interaction between size group and fish species also had significant effect, meaning that depth preference of the species was also dependent on the size of fish. The interaction between size group and surface temperature or surface temperature and fish species was not significant (Table 2). The Tukey HSD test showed there was a significant difference in depth choice between all Arctic char and brown trout size groups, except for Arctic char in group 4 and brown trout in group 4 (Appendix 3). Between the Arctic char size groups there was a significant difference in depth choice between all size groups except group 1 and 2, group 2 and 3, group 2 and 4 and group 3 and 4. Between the brown trout size groups no significant difference in depth choice could be seen between the size groups except for group 2 and 4 and group 3 and 4 (Appendix 3). Arctic char in size groups 1 and 4 tend to live at a wider range of depths compared to the Arctic char in size groups 2 and 3 (Figure 4). Arctic char tends to live deeper compared to brown trout (Figure 4).

Temperature at catch was also significantly affected by size groups as well as fish species identity (Table 2). The interaction between the two was also significant, meaning that temperature preference of the species was also dependent on the size of fish (Table 2). The Tukey HSD test showed there was a significant difference in temperature at catch between all Arctic char and brown trout size groups, except for Arctic char in group 3 and brown trout in group 1, Arctic char in group 4 and brown trout in group 1 and Arctic char in group 4 and brown trout in group 4 (Appendix 3). Between the Arctic char size groups there was a significant difference between all size groups except group 1 and 2, group 1 and 4, group 2 and 4 and group 3 and 4. Between the brown trout size groups no significant difference could be seen between any of the size groups (Appendix 3). The Arctic char in size group 1 and 4 tend to live in a wider range of temperatures compared to the Arctic char in size group 2 and 3 (Figure 8). Arctic char tends to live in colder water compared to brown trout (Figure 6 and 7).

Table 2. Results for the ANOVA analysis of habitat selection for the Arctic char in Abiskojaure and Stor-Björsjön with degrees of freedom, F-values and p-values

	Lake	**Factor**	**df**	**F - value**	**p - value**
Depth	Abiskojaure	Size group	4	62.455	< **0.001**
		Surface temperature	1	3.284	0.0723
		Size group * surface temperature	4	0.654	0.6252
	Stor-Björsjön	Fish species	1	169.075	< **0.001**
		Size group	3	4.337	**0.0064**
		Surface temperature	1	6.957	**0.0097**
		Fish species * size group	3	8.933	< **0.001**
		Fish species * surface temperature	1	0.148	0.701
		Size group * surface temperature	3	0.159	0.923
Temperature	Abiskojaure	Size group	4	106.4	< **0.001**
	Stor-Björsjön	Fish species	1	558.912	< **0.001**
		Size group	3	18.770	< **0.001**
		Fish species * size group	3	5.178	**0.00146**

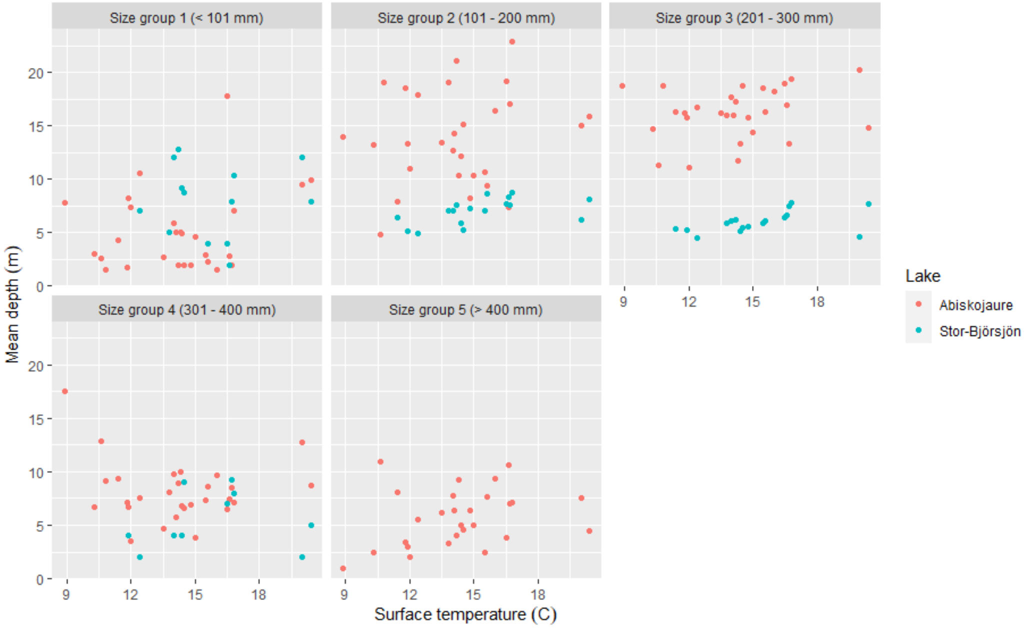

Figure 3. Mean catch depth for the Arctic char in the size groups 1, 2, 3, 4, and 5 in Abiskojaure (max depth 35 m) and Stor-Björsjön (max depth 15 m) in relation to the surface temperature

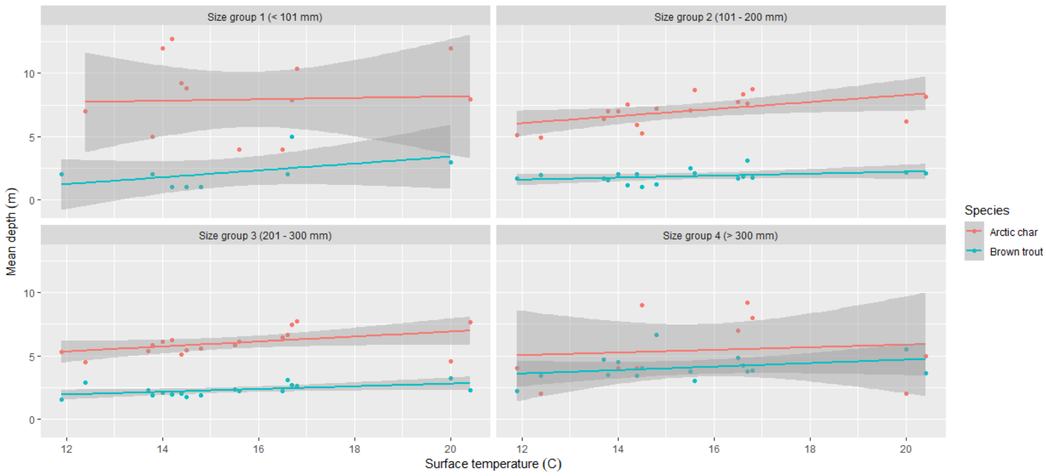

Figure 4. Mean catch depth for the Arctic char and brown trout in the size groups 1, 2, 3 and 4 in Stor-Björsjön (max depth 15 m) in relation to the surface temperature

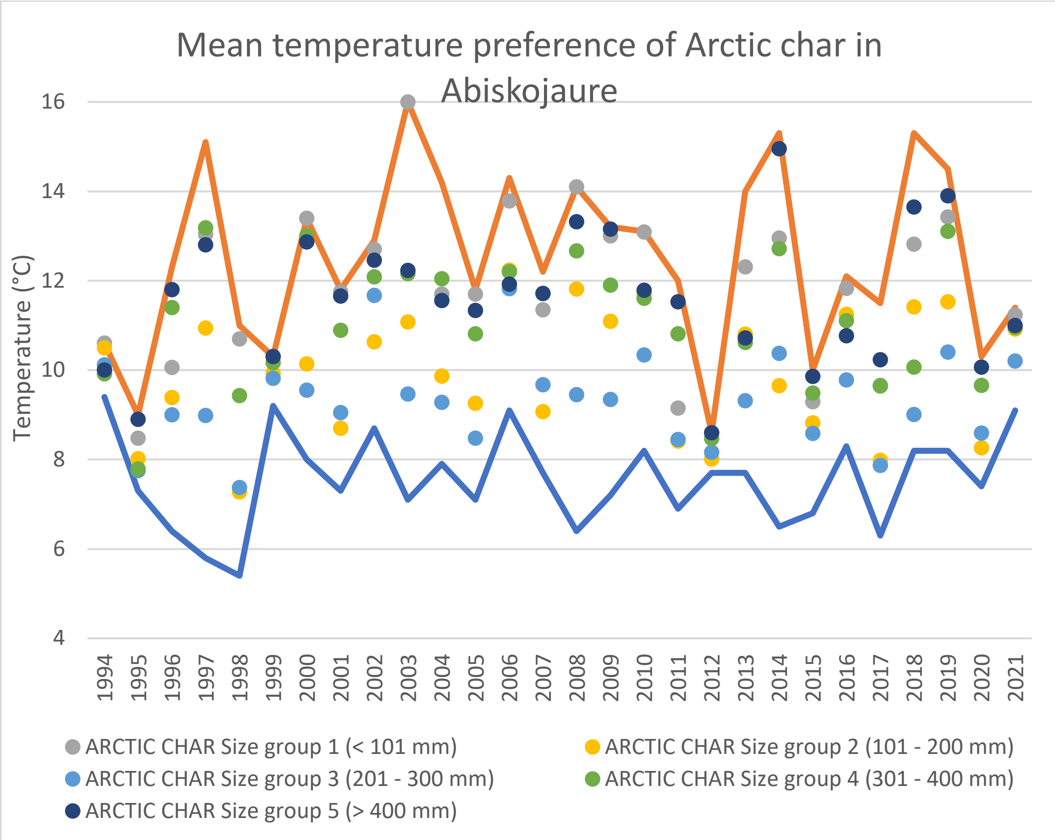

Figure 5. Mean catch temperature for the Arctic char in the size groups 1, 2, 3, 4, and 5 in Abiskojaure. The two lines represent the highest and lowest temperature available in the lake

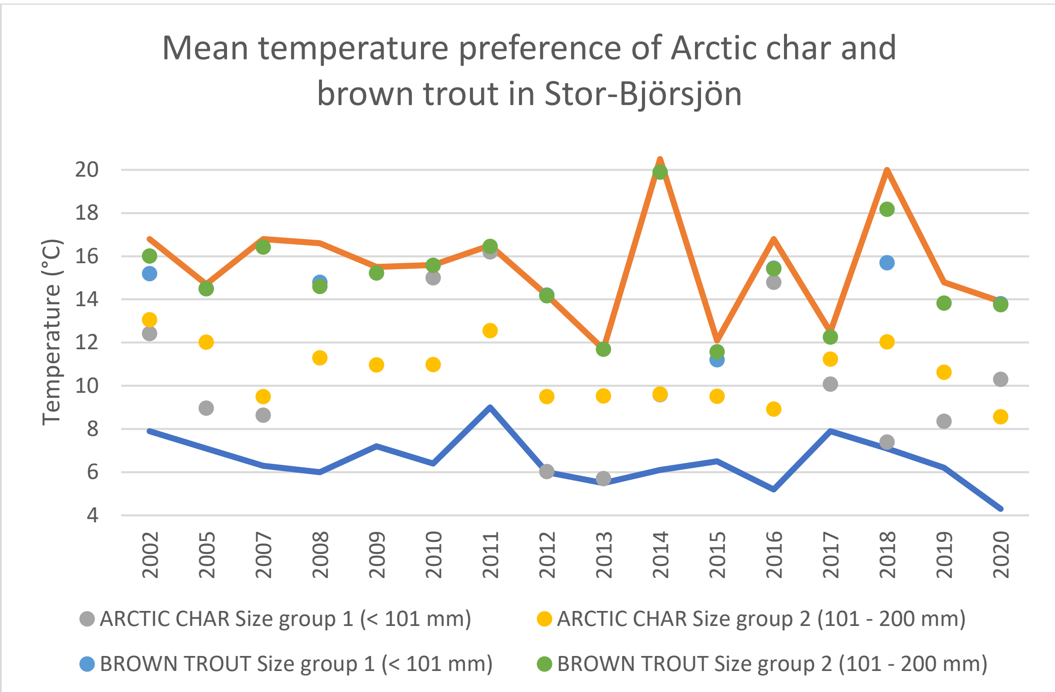

Figure 6. Mean catch temperature for the Arctic char and brown trout in the size groups 1 and 2 in Stor-Björsjön. The two lines represent the highest and lowest temperature available in the lake

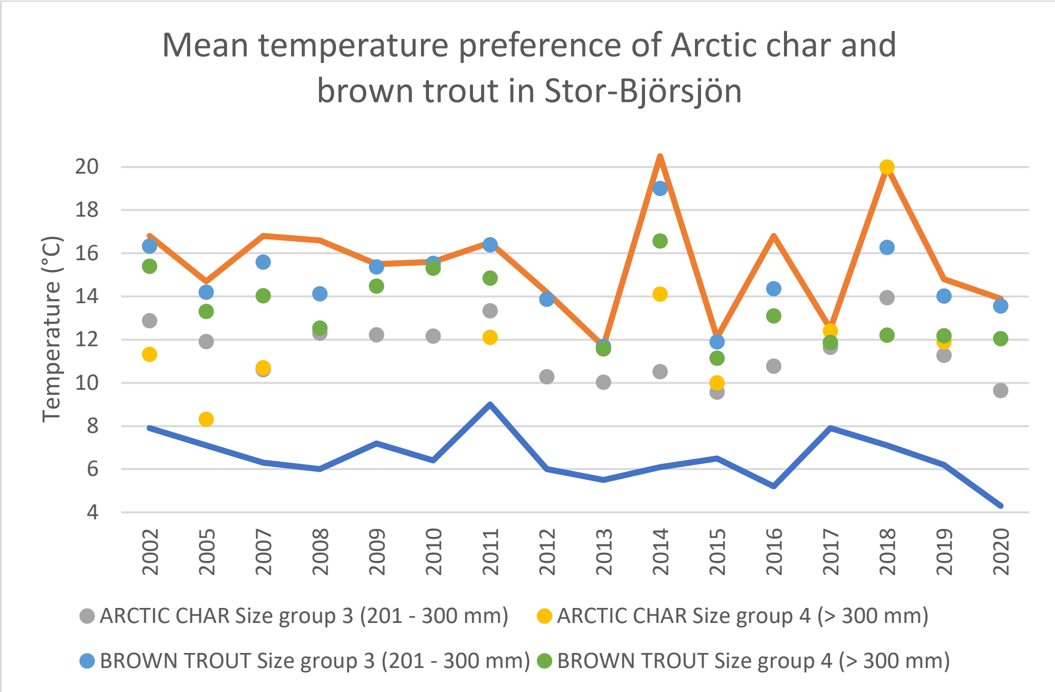

Figure 7. Mean catch temperature for the Arctic char and brown trout in the size groups 3 and 4 in Stor-Björsjön. The two lines represent the highest and lowest temperature available in the lake

4.2 Stomach content

For Arctic char, the stomach content was significantly affected by the interaction of lake and size group (PERMANOVA pseudo $F_{(1,126)} = 1.9363$, $p = 0.033$, Figure 11). In Abiskojaure the main food item in the Arctic char's stomach content was crustaceans (Figure 8). In Stor-Björsjön the main food item for Arctic char were pelagic zooplankton and *Diptera* (mainly *Chironomidae* species, both larvae and pupae) (Figure 9). The Arctic char in size group 3 and 4 in Abiskojaure primarily fed on crustaceans, but the fish in size group 3 also fed on some *Bythotrephes* and terrestrial insects (Figure 11). In Stor-Björsjön the Arctic char in size groups 2 and 3 primarily fed on pelagic zooplankton and mollusks, the fish in size group 2 also fed on *Eurycercus* and the fish in size group 3 *Diptera* (Figure 11). In general the Arctic char in Abiskojaure fed on fewer and larger types of food compared to the Arctic char in Stor-Björsjön (Figure 11).

In Stor-Björsjön, the stomach content was significantly affected by the interaction of species and size group (PERMANOVA pseudo $F_{(3,103)} = 1.9782$, $p = 0.016$, Figure 12). In Stor-Björsjön the main food item in the Arctic char's stomach content was pelagic zooplankton and *Diptera* (Figure 9), while it was larger insects, both predator sensitive macroinvertebrates and terrestrial insects for brown trout (Figure 10). The brown trout in size groups 2 and 3 primarily fed on terrestrial insects, PSM, crustaceans and other while the Arctic char in size group 2 and 3 mainly fed on pelagic zooplankton, mollusks, *Diptera* and *Eurycercus* (Figure 12). The Arctic char in size group 3 had a slight overlap with brown trout since they feed on predator sensitive macroinvertebrates (Figure 12). In comparison, the brown trout fed on fewer and larger types of food compared to the Arctic char in Stor-Björsjön (Figure 12).

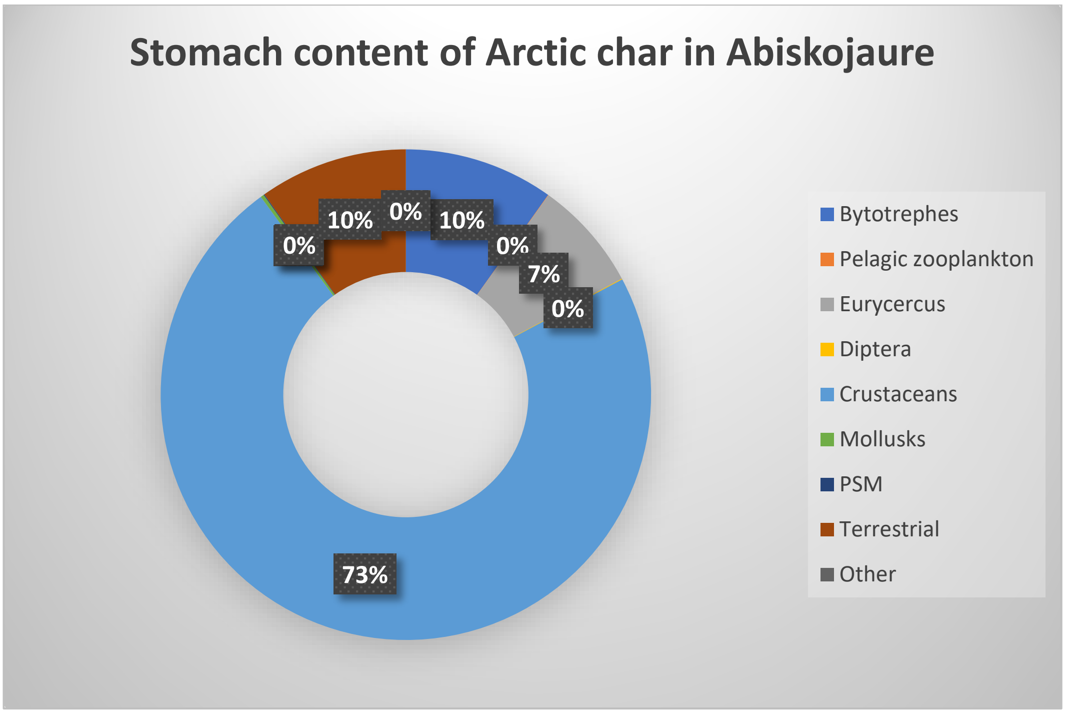

Figure 8. Mean proportion of the stomach content for the Arctic char in Abiskojaure (years 2018, 2020 and 2021)

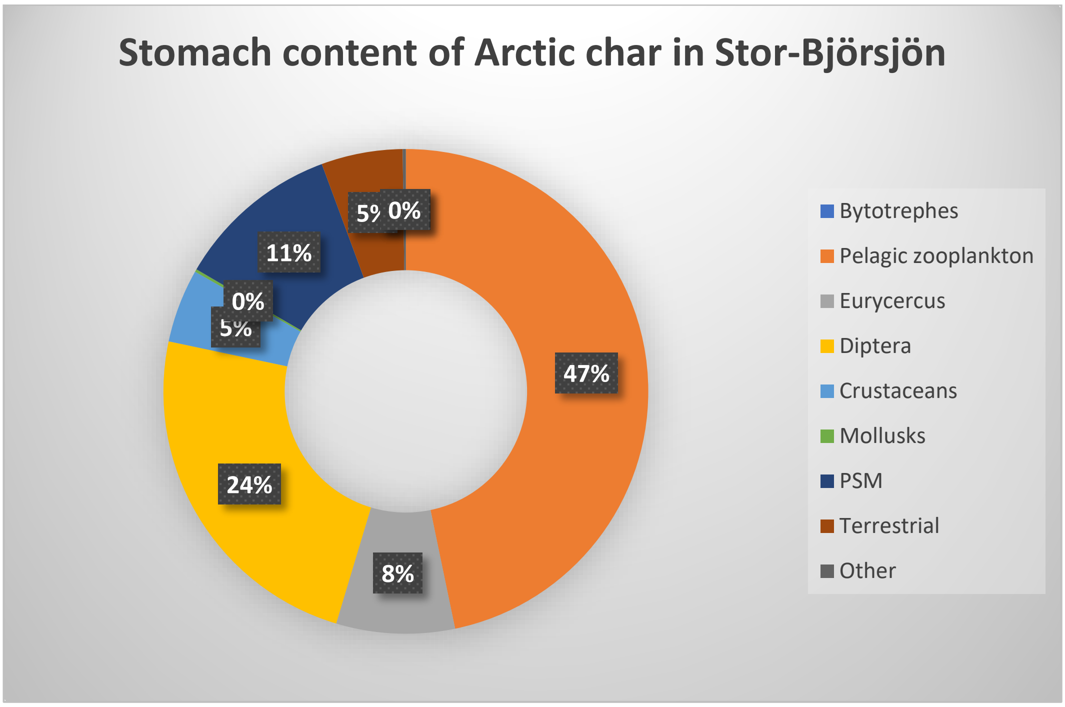

Figure 9. Mean proportion of the stomach content for the Arctic char in Stor-Björsjön (years 2018, 2020 and 2021)

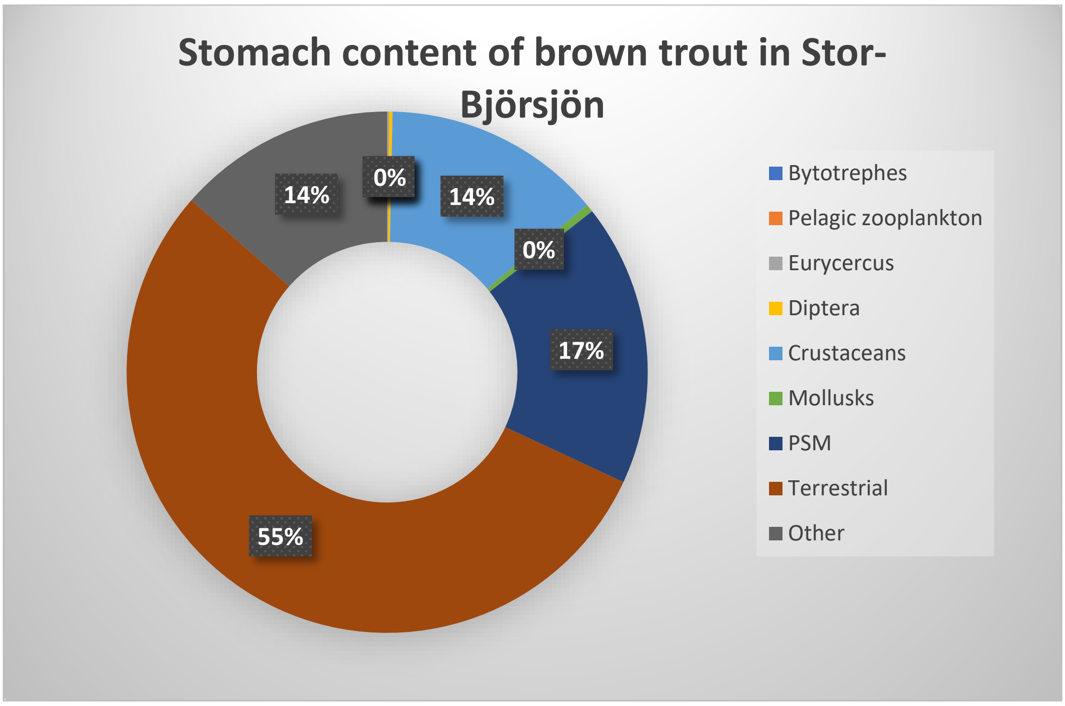

Figure 10. Mean proportion of the stomach content for the brown trout in Stor-Björsjön (year 2018)

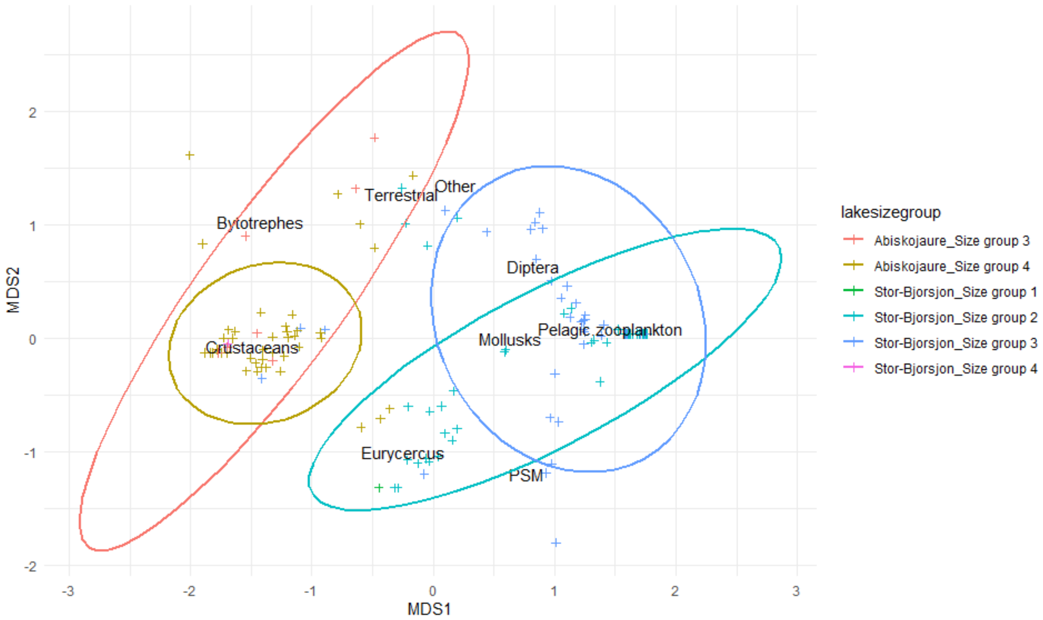

Figure 11. NMDS (stress = 0.12) showing stomach content for the Arctic char in Abiskojaure and Stor-Björsjön for the different size groups. For Stor-Björsjön size group 1 and 4 there were not enough points to create an ellipse

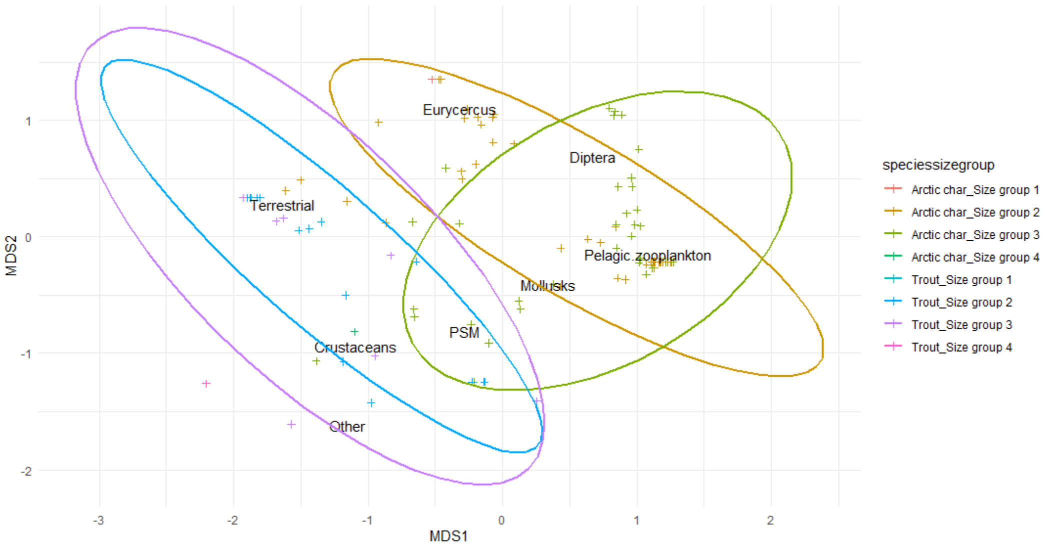

Figure 12. NMDS (stress = 0.12) showing stomach content for the Arctic char and brown trout in Stor-Björsjön for the different size groups. For the Arctic char and brown trout in size groups 1 and 4 there were not enough points to create and ellipse

4.3 Growth determination

In Abiskojaure the relationship between mean annual growth and age was not affected by temperature (warm/cold years, ANCOVA: $F_{(1,13)} = 0.002$, p=0.964, Figure 13). Overall, mean annual growth decreased with age (Slope = -11.681, $R^2 = 0.70$, p <0.001). In Stor-Björsjön the relationship between mean annual growth and age was affected by temperature (ANCOVA: $F_{(1,17)} = 5.797$, p=0.028, Figure 14). In Stor-Björsjön mean annual growth did not significantly change with age in cold years ($Slope_{cold} = -2.787$, $R^2 = 0.32$, p = 0.0678), but mean annual growth did significantly decrease with age in warm years ($Slope_{cold} = -8.363$, $R^2 = 0.71$, p = 0.002). The mean annual growth for Arctic char is higher in warm years for young fish (0+ and 1+) but lower for larger fish (3+ and 4+) compared to colder years (Figure 14).

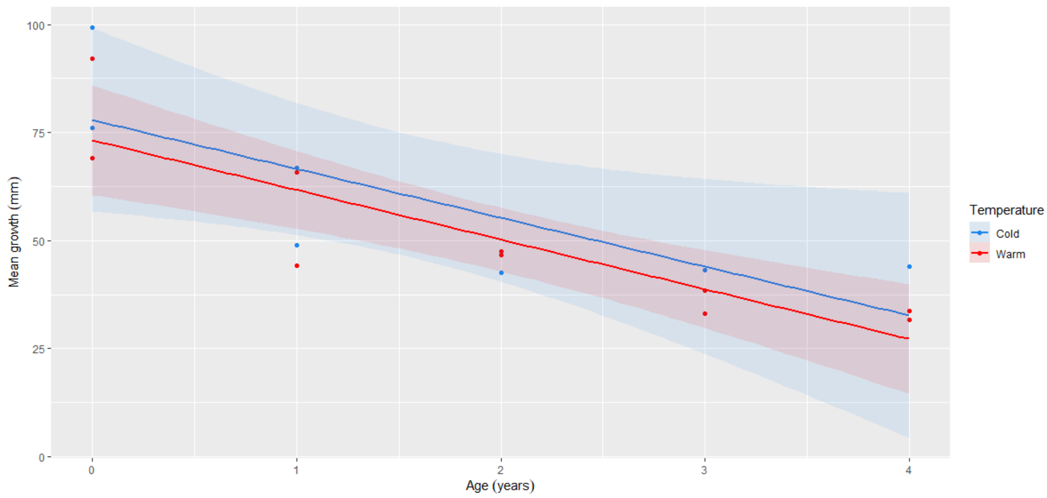

Figure 13. Mean annual growth in relation to warm and cold years for the Arctic char in Abiskojaure

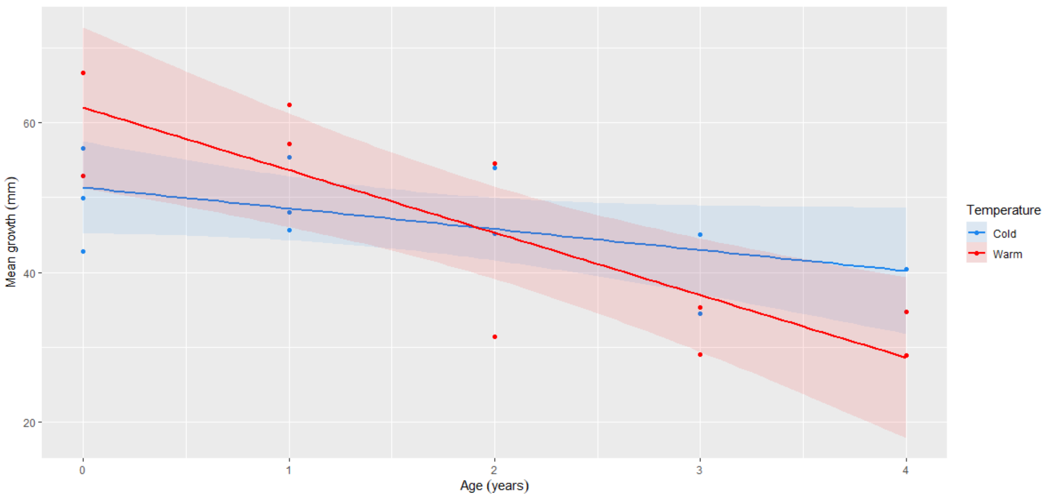

Figure 14. Mean annual growth in relation to warm and cold years for the Arctic char in Stor-Björsjön

5. Discussion

5.1 Habitat selection

The results from Abiskojaure did not reveal any effects of surface temperature on the depth preference for Arctic char, but the habitat use differed between differently sized fish. In Abiskojaure the Arctic char in size group 1 (< 101 mm), 4 (301 – 400 mm) and 5 (> 400 mm) inhabited shallower and warmer water compared to the Arctic char in size group 2 (101 – 200 mm) and 3 (201 – 300 mm). The same pattern can be seen in Stor-Björsjön where the Arctic char in size groups 1 (< 101 mm) and 4 (> 300 mm) are found in a wider range of depths, including more shallow areas compared to the Arctic char in size group 2 (101 – 200 mm) and 3 (201 – 300 mm). The Arctic char (and brown trout in Stor-Björsjön) in size group 1 (< 101 mm) are born in the shallow water and stay there during their growing up time. The warmer temperature in shallow water is favourable and the small fish can find shelter and food among the rocks (Klemetsen et al. 2003).

There can be many reasons the larger Arctic char are found at shallow depths. One possibility is that they are cannibalistic or prey on small individuals of other species, (Artdatabanken 2022; Finstad et al. 2006; Klemetsen et al. 2003). That might be the reason bigger fish are found in shallower water, in both Abiskojaure and Stor-Björsjön. However, in the stomach content analysis, fish was only found in one of the fishes stomachs. That fish was a brown trout, and none of the other 42 fishes categorized as size group 4 (301 – 400 mm for Abiskojaure and > 300 mm for Stor-Björsjön) had fish in their stomach. It is hence not very likely that predation was the main reason for the habitat choice of larger fish.

Another reason might be that larger Arctic char have a better chance than small individuals of competing with the brown trout for the food in the littoral zone. The stomach content analysis gives a slight indication of this, where the Arctic char in size group 3 (201 – 300 mm) in Stor-Björsjön had a diet overlap with the brown trout in size groups 2 (101 – 200 mm) and 3 (201 – 300 mm). However, the food niches for the two species are different, and this rather suggests that the competitive situation is a form of interference, where the brown trout is a stronger (more aggressive) competitor, forcing the Arctic char to change its habitat (Forseth et al. 2003; Klemetsen et al. 2003).

Another possible factor is that the gillnet fishing is done just before or at the beginning of the spawning time. The spawning for Arctic char takes place in the autumn months August – January (Artdatabanken 2022) and the gillnet fishing takes place at the end of July – beginning of August. The Arctic char that are ready to spawn might already be in the shallower water and are thus being caught there. However, Arctic char can sexually mature at a small size so if this was the case, we would expect that some fish from size groups 2 (101 – 200 mm) and 3 (201 – 300 mm) are also caught in shallow water. Therefore this reason is unlikely. Thus, the reason that bigger fish are caught in shallow water could depend on different factors or a combination of factors and further studies are needed to determine this.

In Stor-Björsjön there is a trend that both the Arctic char and brown trout inhabit deeper and thus likely colder water when the surface water is warmer. This is in line with my first hypothesis that states that the Arctic char will change their habitat towards deeper/colder water when water temperatures rise. However, in Abiskojaure the habitat choice of Arctic char was not affected by surface temperature. The reason that the Arctic char in Stor-Björsjön seek deeper/colder water as the surface water gets warmer might be that the water temperatures here reach and exceed the optimal temperature range of the Arctic char. The optimal temperature for Arctic char is somewhere between 14.4 ℃ - 17.2 ℃, but in reality, this number depends on resource levels and is believed to be lower (Hein et al. 2012). The surface water in Stor-Björsjön sometimes reach temperatures up to 20 ℃, which might lead the Arctic char to seek colder water in deeper parts of the lake. Abiskojaure is situated so far north, meaning the water is relatively cold. The water temperature in Abiskojaure rarely reaches 16 °C in the surface, meaning the optimal temperature for Arctic char is never exceeded. Thus, there is no reason for the Arctic char to utilize deeper/colder waters. In the future however, with expected climate change and warming of waters, occurring in the Arctic region, the Arctic char will likely need to use greater depths in Abiskojaure as well.

In Stor-Björsjön the presence of brown trout in the lake could make the Arctic char utilize a different habitat. This result is in line with my second hypothesis that states that the Arctic char, in presence of brown trout, will utilize deeper water. There is a slight overlap in depth preference for the Arctic char in size group 4 (> 300 mm) with the brown trout. However this might link back to what was previously discussed why the larger Arctic char can be found in shallower water. The brown trout prefers to live in the littoral zone, and in general is a much stronger competitor than Arctic char for this habitat (Klemetsen et al. 2003). If competition from brown trout is too strong, and there are not enough resources, Arctic char might seek colder/deeper water to lower their metabolic rates. This can be supported by the growth analysis which shows a lower annual growth for the younger and smaller (< 3+) Arctic char in Stor-Björsjön, compared to young (< 3+) Arctic char in Abiskojaure. When the Arctic char grow larger and older, they have a better chance of competing with brown trout for resources and can thus grow better. With the brown trout being a stronger competitor for littoral resources during the ice-free period, the future for Arctic char in some waters is uncertain (Urban et al. 2011). Predicted climate change and shifts in seasonal patterns in the Arctic region will likely result in shorter winters and longer summers (Bintanja & Van der Linden 2013) and should this happen, risk is that competition from brown trout will be too strong for the Arctic char to co-exist in some lakes (Urban et al. 2011).

The habitat selection of the Arctic char in this study was based on both catch depth and temperature for each lake separately. The two lakes differ quite a lot in what is available both depth and temperature wise. Abiskojaure is situated much further north than Stor-Björsjön and the temperatures in Abiskojaure rarely reach 16 °C in the surface water, while this is about the average temperature for the surface water in Stor-Björsjön during the study time. Abiskojaure is also a lot deeper than Stor-Björsjön with the maximum depth being 35 m compared to Stor-Björsjöns 15 m. So the comparison was done within each lake, and it is hard to completely disentangle the effect of brown trout and temperature here.

5.2 Stomach content

The diet of the Arctic char differed substantially between the two lakes. In Abiskojaure, the main proportion of the Arctic char's diet consisted of crustaceans such as *Gammarus pulex* and *Lepidurus*, while in Stor-Björsjön it consisted mainly of pelagic zooplankton and *Diptera*. The reason for this difference is likely the absence of brown trout in Abiskojaure, and its presence in Stor-Björsjön. Since the Arctic char is the only species present in Abiskojaure they will mostly utilize the littoral zone, where food items like *Gammarus* and *Lepidurus* can be found. In contrast, when brown trout is present, the Arctic char will be outcompeted by the brown trout and have to utilize the pelagic zone. In the pelagic zone, pelagic zooplankton is the most common food item, and therefore also the most commonly found in Arctic char from Stor-Björsjön. These results are in accordance with previous studies (Klemetsen et al. 2003; Langeland et al.

1991; Urban et al. 2011), as well as my hypothesis that states that the Arctic char would modify their diet, where brown trout is present. The Arctic char in size group 3 (201 – 300 mm) had a slight diet overlap with the brown trout, and this can link back to what was previously discussed about the larger Arctic char having better chance of competing with brown trout for resources compared to smaller Arctic char.

The diet preference for Arctic char living in sympatry with brown trout varies between lakes, but also with prey population densities (Skoglund et al. 2013). In general, Arctic char will feed on pelagic zooplankton species such as *Bosmina*, *Daphnia* and also larger predatory zooplankton such as *Bythotrephes*. What seems to be a common factor is that the Arctic char also target the larger individuals of these preferred species (Skoglund et al. 2013). Therefore the composition of the prey species might vary between years. Another factor is that the stomach content in this study is from a certain time of the year. The availability in prey species might vary over seasons as well, affecting the diet choice of the fish. To get more precise results, stomach content analysis should be made over a longer time series, both within and over years.

5.3 Growth determination

In Stor-Björsjön, growth did not change with age of the fish in cold years, but in warm years, the growth decreased with the age and size of fish. This can be linked back to the fact that water temperatures in Stor-Björsjön sometimes exceed the optimal range for Arctic char. These years the warm water temperatures will have a negative impact on the older Arctic char, who will not be able to cope with the higher cost with higher metabolic rates (Budy & Luecke 2014). The larger Arctic char will have to eat more to fulfil the higher energy requirements in warmer water, and therefore lose more energy in search for food compared to when the water is colder. This will result in a lower annual growth. The younger Arctic char however can benefit from the warmer water, as they do not have to eat as much more to fulfil the higher metabolic rates. These results depend on more factors than just warm/cold years. One of them is food availability in the lake, what prey items are available and in what densities. Should the prey populations be really large, chances are that the growth of larger Arctic char will not be as negatively affected. At the same time, if prey populations are low, risks are they will be more negatively affected, and perhaps also the smaller Arctic char will be negatively affected. In Stor-Björsjön the main food item for the Arctic char is pelagic zooplankton, which is a much smaller food item compared to crustaceans, which is the main food item for the Arctic char in Abiskojaure. The Arctic char have to eat more food items to fulfil the energy needs in Stor-Björsjön compared to

Abiskojaure, and might also have to spend more energy finding the food. Further this also depends on the competitive situation in the lake. Where the brown trout is present, they compete with the Arctic char for the benthic resources. In Abiskojaure, where brown trout is absent, they feed on larger food items and might be able to benefit from higher temperatures compared to Stor-Björsjön. Further studies are needed to study the growth in relation to both prey abundance and competition in more detail. The result from Stor-Björsjön is in accordance with my hypothesis, which stated that younger Arctic char will benefit more from warmer water and grow faster, while older Arctic char will be negatively affected.

In Abiskojaure the younger fish had higher mean annual growth compared to the older fish, for both warm and cold years. The reason that young fish have higher annual growth compared to older fish is that they can invest all their resources into growth while larger fish also invest some resources in spawning. The fact that warm years did not have a negative effect on older fish in Abiskojaure might link back to what was previously discussed about the temperatures in Abiskojaure not exceeding the optimal temperature range for Arctic char. The warmest years do not reach high enough temperatures for it to affect the behaviour and metabolism of the Arctic char negatively.

5.4 Limitations

The main limitation is that only two lakes were studied. When only comparing two lakes there are many (biotic and abiotic) factors that can affect the results, and the results might not be generally applicable. Abiskojaure and Stor-Björsjön are located in different parts of Sweden and also differ quite a lot in both size and depth. Studying more lakes of similar characteristics will give a better understanding of the effects of climate change on the Arctic char as well as better comparison of the competitive situation with brown trout. Further limitations are regarding few fish analysed for the stomach content and the growth determination. For the stomach content analysis, fish from only two years were studied in Abiskojaure, and from three years in Stor-Björsjön. Regarding brown trout in Stor-Björsjön, this data came from 25 fish in 2018. To get better results, stomach content from more years could be studied as food availability between years might vary quite a bit. To make a better comparison of the stomach content of Arctic char and brown trout these should come from the same years, for the same reason as mentioned above. Also, all the fish have been caught in the autumn and therefore the results only reflect the fish' diet in autumn. To get a better understanding, stomach content analysis could be done multiple times a year to also detect differences between seasons. The growth determination was done on three Arctic char in each age class for each year. To get more secure results, otoliths from more fish, preferably from a wide spread of ages in the warm and cold years should have been looked at. Also, the growth of fish is affected by many more factors than warm/cold years, such as food availability and competition, and by comparing more lakes, the effects of these other factors can be minimized.

5.5 Conclusions

My results indicate that future global warming may have a negative effect on the Arctic char population in Sweden. In Stor-Björsjön, where the water temperatures sometimes exceed the optimal temperature range for Arctic char these negative effects can be seen. The Arctic char here inhabit deeper water with higher surface temperatures, showing they prefer colder water. The growth of larger Arctic char is also lower in warmer years compared to cold in Stor-Björsjön, further indicating the preference of colder water. The presence of brown trout also makes the Arctic char inhabit deeper/colder water as the brown trout is a stronger competitor for littoral resources. Furthermore, this competition from brown trout may have a larger effect in the future with longer ice-free periods, further worsening the situation for the Arctic char.

Climate change is likely to have a negative effect on the Arctic char population in Sweden. The warmer water will likely disfavour the Arctic char who is adapted to colder conditions. It will also give the brown trout even better conditions to compete with the Arctic char. But there are many more factors affecting the Arctic char population, and it is still unclear what will happen in the future. Further studies are required to understand the Arctic char's situation better and to take measures to preserve the species to as large extent as possible.

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Popular science summary

Some of the effects of climate change are increased global temperature and changed seasonal patterns. The areas that are most vulnerable for these changes are the arctic regions. Arctic char is a common cold-water species with the most northern distribution of all freshwater fish species. The distribution area of Arctic char in Sweden could decrease with more than half in 2100 as a result of climate change and its consequences. Here, I have studied how climate change will affect the habitat- and food choice as well as the growth of Arctic char, both in lakes with (Abiskojaure) and without (Stor-Björsjön) brown trout present. My results show that the smallest and largest Arctic char in Abiskojaure were caught in shallower water compared to fish of intermediate size. In Stor-Björsjön the smallest and largest Arctic char were caught at a wider range of depths compared the middle size fish. The Arctic char in Stor-Björsjön also tended to stay deeper compared to the brown trout. The Arctic char's diet in Abiskojaure mainly consisted of crustaceans. In Stor-Björsjön pelagic zooplankton were the main food source for the Arctic char, while the brown trout mainly fed on larger insects. The annual growth of Arctic char was the highest among small fish, and it slowly decreased with the age of the fish. In Stor-Björsjön, warm years had a beneficial effect on the growth of the small fish, while the growth of larger fish were negatively affected by the warmer water. Climate change, and the consequences of it, are likely to have a negative effect on the Arctic char population in Sweden. When water temperatures exceed the comfort temperature for Arctic char, they tend to inhabit deeper water, and the growth of bigger fish is negatively affected, showing that the species prefer colder water. Where brown trout is present the two species inhabit different parts of the lake. The brown trout inhabit the shallower areas and the Arctic char the deeper parts. The brown trout is a stronger competitor for resources during the ice-free period and should these periods be longer, as a result of climate change, the competition pressure might hold the Arctic char population back. It is unclear how climate change will affect the Arctic char population in the future and further studies are required to understand the situation better and to take measures to preserve the species to as large extent as possible.

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Appendix

Appendix 1. Number of individuals in the different size groups for Arctic char in Abiskojaure (years 1994 – 2021) and Arctic char and brown trout in Stor-Björsjön (years 2002 – 2021)

Lake	**Size group**	**Number of individuals Arctic char**	**Number of individuals Brown trout**	**Number of individuals Total**
Abiskojaure	1 (< 101 mm)	245	-	245
	2 (101 – 200 mm)	1586	-	1586
	3 (201 – 300 mm)	1403	-	1403
	4 (301 – 400 mm)	649	-	649
	5 (> 400 mm)	157	-	157
Stor-Björsjön	1 (< 101 mm)	73	9	82
	2 (101 – 200 mm)	659	291	950
	3 (201 – 300 mm)	483	257	740
	4 (> 300 mm)	15	68	83

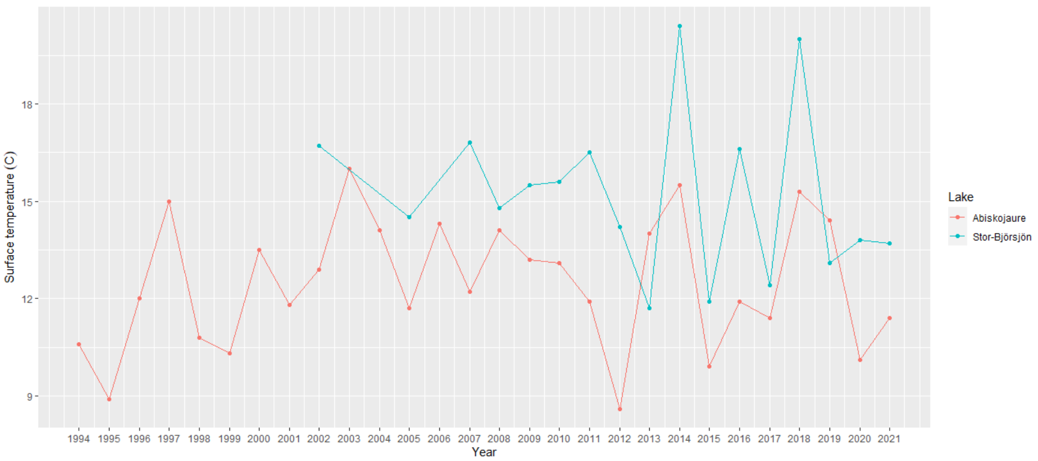
Appendix 2. Results for the Tukey HSD-test conducted on catch depth and catch temperature of Arctic char in Abiskojaure with p-values

		Factor	**p - value**
Abiskojaure	Depth	Gr 1 * Gr 2	**0.000**
		Gr 1 * Gr 3	**0.000**
		Gr 1 * Gr 4	**0.007**
		Gr 1 * Gr 5	0.949
		Gr 2 * Gr 3	0.091
		Gr 2 * Gr 4	**0.000**
		Gr 2 * Gr 5	**0.000**
		Gr 3 * Gr 4	**0.000**
		Gr 3 * Gr 5	**0.000**
		Gr 4 * Gr 5	0.058
	Temperature	Gr 1 * Gr 2	**0.000**
		Gr 1 * Gr 3	**0.000**
		Gr 1 * Gr 4	**0.000**
		Gr 1 * Gr 5	0.336
		Gr 2 * Gr 3	**0.000**
		Gr 2 * Gr 4	**0.000**
		Gr 2 * Gr 5	**0.000**
		Gr 3 * Gr 4	**0.000**
		Gr 3 * Gr 5	**0.000**
		Gr 4 * Gr 5	0.547

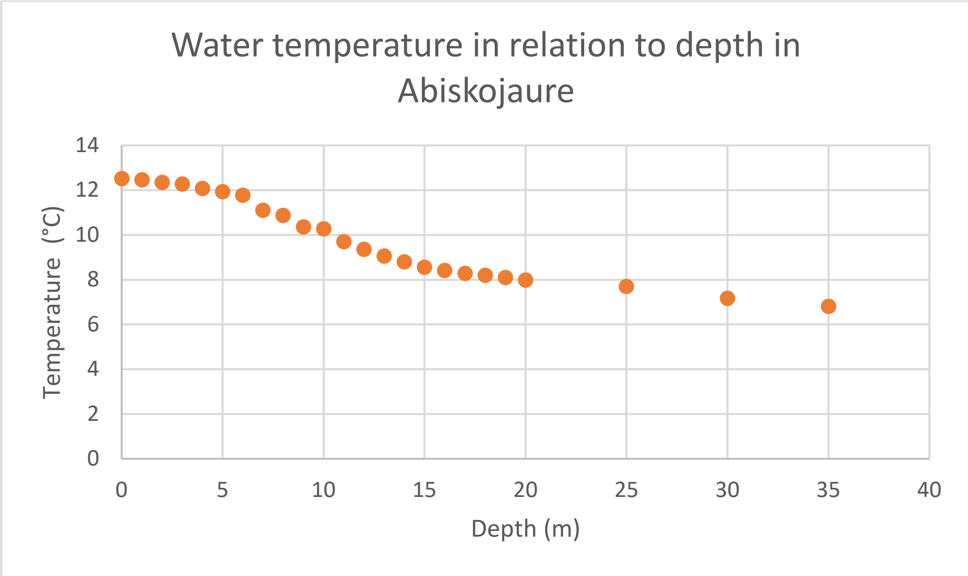
Appendix 3. Results for the Tukey HSD-test conducted on catch depth and catch temperature of Arctic char and brown trout in Stor-Björsjön with p-values

		Factor	p - value
Stor-Björsjön	Depth	AC Gr 1 * AC Gr 2	0.784
		AC Gr 1 * AC Gr 3	**0.035**
		AC Gr 1 * AC Gr 4	**0.009**
		AC Gr 1 * BT Gr 1	**0.000**
		AC Gr 1 * BT Gr 2	**0.000**
		AC Gr 1 * BT Gr 3	**0.000**
		AC Gr 1 * BT Gr 4	**0.000**
		AC Gr 2 * AC Gr 3	0.619
		AC Gr 2 * AC Gr 4	0.232
		AC Gr 2 * BT Gr 1	**0.000**
		AC Gr 2 * BT Gr 2	**0.000**
		AC Gr 2 * BT Gr 3	**0.000**
		AC Gr 2 * BT Gr 4	**0.000**
		AC Gr 3 * AC Gr 4	0.986
		AC Gr 3 * BT Gr 1	**0.000**
		AC Gr 3 * BT Gr 2	**0.000**
		AC Gr 3 * BT Gr 3	**0.000**
		AC Gr 3 * BT Gr 4	**0.018**
		AC Gr 4 * BT Gr 1	**0.001**
		AC Gr 4 * BT Gr 2	**0.000**
		AC Gr 4 * BT Gr 3	**0.000**
		AC Gr 4 * BT Gr 4	0.426
		BT Gr 1 * BT Gr 2	0.999
		BT Gr 1 * BT Gr 3	0.999
		BT Gr 1 * BT Gr 4	0.119
		BT Gr 2 * BT Gr 3	0.993
		BT Gr 2 * BT Gr 4	**0.004**
		BT Gr 3 * BT Gr 4	**0.045**
	Temperature	AC Gr 1 * AC Gr 2	0.128
		AC Gr 1 * AC Gr 3	**0.000**
		AC Gr 1 * AC Gr 4	0.267
		AC Gr 1 * BT Gr 1	**0.000**
		AC Gr 1 * BT Gr 2	**0.000**
		AC Gr 1 * BT Gr 3	**0.000**
		AC Gr 1 * BT Gr 4	**0.000**
		AC Gr 2 * AC Gr 3	**0.004**
		AC Gr 2 * AC Gr 4	0.911
		AC Gr 2 * BT Gr 1	**0.005**

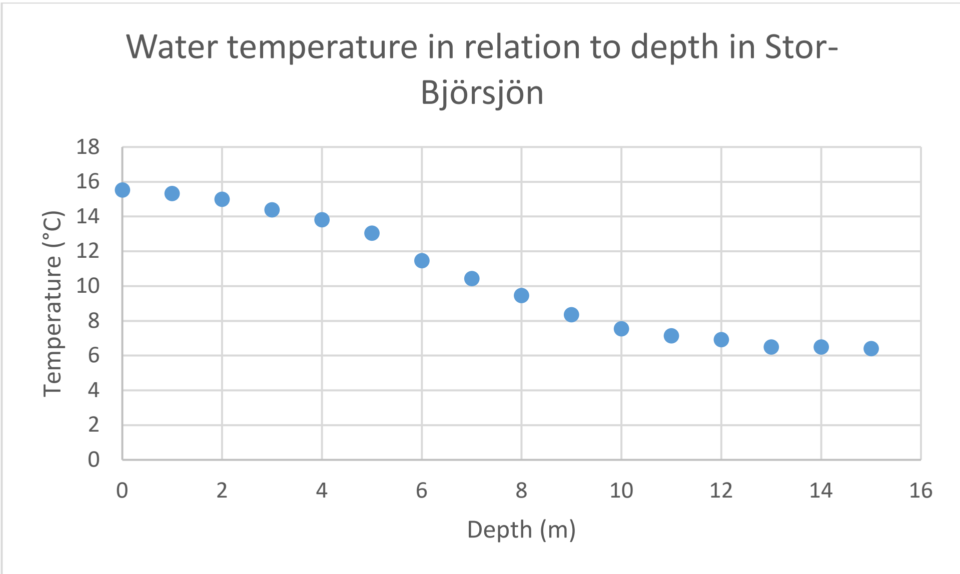
AC Gr 2 * BT Gr 2	**0.000**
AC Gr 2 * BT Gr 3	**0.000**
AC Gr 2 * BT Gr 4	**0.000**
AC Gr 3 * AC Gr 4	0.999
AC Gr 3 * BT Gr 1	0.053
AC Gr 3 * BT Gr 2	**0.000**
AC Gr 3 * BT Gr 3	**0.000**
AC Gr 3 * BT Gr 4	**0.000**
AC Gr 4 * BT Gr 1	0.360
AC Gr 4 * BT Gr 2	**0.001**
AC Gr 4 * BT Gr 3	**0.007**
AC Gr 4 * BT Gr 4	0.250
BT Gr 1 * BT Gr 2	0.999
BT Gr 1 * BT Gr 3	0.999
BT Gr 1 * BT Gr 4	0.998
BT Gr 2 * BT Gr 3	0.891
BT Gr 2 * BT Gr 4	0.067
BT Gr 3 * BT Gr 4	0.452



Appendix 4. Surface temperatures for both Abiskojaure (years 1994 – 2021) and Stor-Björsjön (years 2002 – 2021)



Appendix 5. Water temperature in relation to depth in Abiskojaure



Appendix 6. Water temperature in relation to depth in Stor-Björsjön

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