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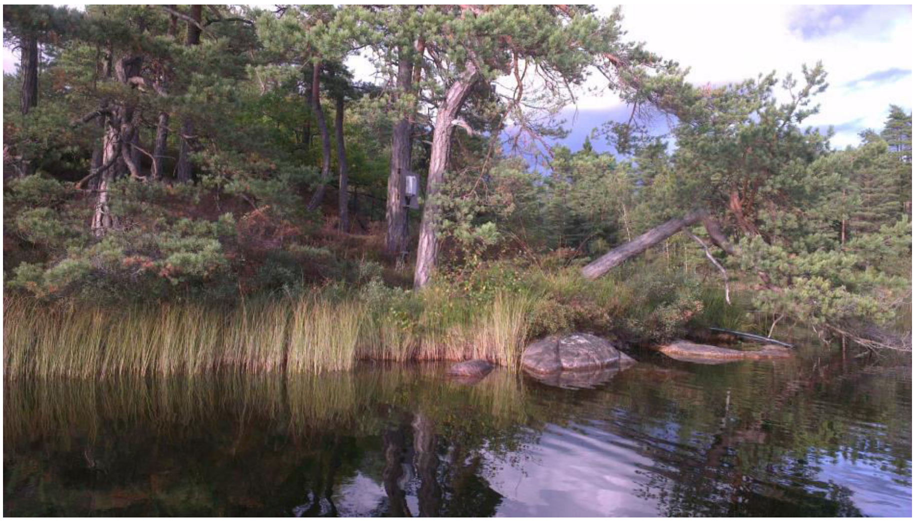
Uppsala, Sweden 2014

Jaclyn C. Martin



Forest harvest effects on mercury in European perch

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Abbreviations

ANCOVA	Analysis of covariance
B	Björntjärn
BK	Brobo-Kroktjärn
CC	Clear-cut
DOC	Dissolved organic carbon
G	Gårdsjön
Fe	Iron
K	Kroktjärn
L	Långtjärn
HgS	Mercuric sulfide
Hg	Mercury
MeHg	Methylmercury
THg	Total mercury
totN	Total nitrogen
TOC	Total organic carbon
totP	Total phosphorus
[Hg]	Mercury concentration

Abstract

Previous studies done on water chemistry found that clear-cutting forests increases methylmercury (MeHg) concentrations. In recent years, few studies have been conducted on what effect forestry operations have on mercury (Hg) concentrations in biota, more specifically on fish. Predictions were made that Hg concentrations would increase by 10-25% in fish after clear-cutting. In order to determine if the predictions were accurate, a study was done on the effects of Hg in perch after clear-cutting around six study lakes throughout Sweden between the years 2010-2013. Fish samples were taken before (2010) and after (2011 and 2013) the clear-cutting took place. There was a significant increase in Hg concentration in relation to fish size. There was an increase of 10% in fish Hg overall post-harvest, when length, weight, and age were used as covariates in the analysis of clear-cut effects. The lakes with higher clear-cut areas within their catchments were also higher in mean Hg concentration ([Hg]) post-harvest, whereas the lakes with the lowest clear-cut areas were found lower in mean [Hg] post-harvest. These results are consistent with previous studies done on biota, water, and soil in boreal lake catchments. These findings give insight on how forest harvest can have a negative impact on the surrounding catchments and on the lake fish Hg concentrations. Further studies should be conducted on the role of the bacteria, zooplankton, and nitrogen isotopes within these catchments to better explain how Hg is released and methylated after forest harvest, moving from the water into the aquatic food web.

Popular Science Summary

Does mercury affect freshwater perch?

What's going on with the fish?

Fish are an important part of the ecosystem and constitute an important food resource for humans, as well as wildlife. A large problem with having a fish diet is that people must restrict serving amounts because of the mercury levels in the muscle tissue. The fish bioaccumulate the mercury from many different places, but human activities, like forestry, are suspected to enhance Hg accumulation in fish.

How do you link cutting down trees to unsafe fish consumption?

Forests are important ecosystems throughout the boreal region. Trees utilize rainwater to grow instead of letting it all run into the lakes and rivers. When the trees are cut down, the excess water is retained in the soil. This effect creates new environmental conditions which allow bacteria to form Hg into methylmercury, a harmful and bioaccumulating substance. Methylmercury moves through the food web into smaller animals that will eventually become dinner for the fish.

How can you measure this?

A team of scientists went out to several lakes and caught fish before and after the trees in the lake catchment were cut down. Data obtained from the field revealed that there was a 10% increase in mercury levels compared to the concentrations found before the clear-cut took place. This was the first time that forestry in Nordic countries was shown to correspond with fish Hg levels. Previously, scientists predicted that there would be a 10-25% increase. This new evidence is showing that those initial predictions were true.

Could other things be influencing the higher levels of mercury?

The mercury bioaccumulation problem is a complex process with several mechanisms that work together. We now know that forestry plays a role in these processes. It is well known that other processes are strongly influencing the mercury levels in the fish. One area that is well known to control accumulation of mercury is the diet of the fish. Tests are now available to figure out where the fish belong on the food chain. This will give scientists a better picture on how forestry affects bioaccumulation of mercury.

1. Introduction

1.1 *Mercury and Forestry*

Sweden is dominated by boreal forests of Norwegian spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). Sweden's economy largely relies on lumber production as an important export. In recent years, forestry practices have raised concerns in scientific communities due to the forestry industry's great ecological impacts. One of these concerns is the possible effects it may have on Hg levels in freshwater and biota after forest clear-cuttings. Several studies have been done throughout Scandinavia, Canada, and the US on the effects of clear-cutting and the effects of Hg mobilization in streams and exposure to biota at the base of the food chain in aquatic ecosystems (Garcia and Carignan, 2005; Bishop et al., 2009; Skyllberg et al., 2009; Eklöf et al., 2012; Murray-Riva et al., 2011; Eklöf et al., 2014). Increased levels of Hg were found in water after clear-cutting. Slight changes in the water chemistry from the clear-cutting can directly affect aquatic chemistry and biota. For instance, higher DOC levels have been recorded after clear-cut logging in Canada (Carignan et al., 2000). Despite the abundance of literature on forestry effects, little has been published about its effects on fish. Because connecting forestry to [Hg] in fish had never been done before in Sweden, the aim of this study was to find the relationship between the two.

Recent studies show a positive correlation between clear-cutting and Hg concentration in runoff (Skyllberg et al., 2009). Furthermore, a study conducted in Sweden showed that MeHg levels were 30-50% higher after a combination of logging and site preparation (Eklöf et al., 2014). A study done on clear-cutting spruce determined monthly concentrations of THg and MeHg were significantly higher (12.02 ng L($^{-1}$) and 0.35 ng L($^{-1}$)) after clear-cutting (Porvari et al., 2003). Forest harvesting increased the total Hg in runoff to the aquatic ecosystems (Bishop et al., 2009). Because of these studies, it is important to look into the biota, especially the fish response to the increased Hg levels.

1.2 *Effects of Clear-cutting on Water Quality and Fish*

Eklöf et al. (2012) found variation in the response to [Hg] levels in the water from different forestry practices that also could be connected to the sensitivity of the forest catchments. Some cases had higher loads of Hg, and in others there were lower loads of Hg after forest clear-cut, leading to variations in Hg methylation and transport. For instance, concentrations of dissolved organic carbon (DOC) and MeHg in the water increased significantly after a new clear-cut in comparison to reference streams (Skyllberg et al., 2009). Environmental problems primarily stem from the transport of Hg from the soil to the water (Driscoll et al., 2013). For instance, clear-cutting disrupts evapotranspiration of the trees and increases the amount of water in soil, which leads to an increase of the water table level to more surficial levels (Bishop et al., 2009). Afterwards, organic matter becomes more saturated and increases the lateral water flow. The water flow then increases the total load into the surface waters of the catchments.

Zooplankton were found containing higher MeHg after forest harvest, but effects on fish were still unknown (Garcia et al., 2007). MeHg bioaccumulates in invertebrates feeding on bacteria and then enters the fish that consume the invertebrates (Stokes and Wren, 1987). Piscivorous fish, which are higher in trophic level, have higher levels of MeHg, a phenomenon that is widely known as biomagnification (Garcia and Carignan, 2005). The ratio of clear-cut area within lake catchments can be related to Hg levels in fish (Garcia and Carignan, 2005). It was consistent with their earlier findings that the logging activities were followed by an increase in biomagnification of Hg in northern pike (Garcia and Carignan, 2000). The bioaccumulation becomes a domino effect, raising health concerns on fish consumption for both larger predatory animals and humans.

1.3 *Mercury in the Environment*

Mercury is a concern to aquatic ecosystems because it can bioaccumulate in organisms, especially in aquatic ecosystems, and can be a dangerous exposure route for fish-eating animals and humans (Scheulhammer et al., 2007). Hg occurs naturally in the environment in bedrock and is deposited as mercuric sulfide (HgS) from volcanoes and forest fires (USGS, 2000). Although Hg exists in nature, human activities, like the use of Hg in gold and silver mining, as well as coal burning, have caused an anthropogenic increase in concentration of the element within the environment (Hylander et al., 2005). Increased concentrations of Hg have been found in the soil, water, and biota that can be attributed to anthropogenic activities. The trend continues as the reliance on industry and fossil fuels rises. In 2013, the Minamata Convention on Hg was signed by over 90 countries which have agreed to reduce Hg emissions from coal power plants, mining, air transport, cell chlor-alkali production, Hg in supplies and products, and wastewater (UNEP, 2013).

Hg is converted into MeHg, a toxic and bioaccumulating form of Hg, mainly through microbial methylation (Compeau et al., 1985). Anoxic environments allow mercury methylating bacteria, i.e. sulfate-reducing bacteria, iron-reducing bacteria, and methanogens, to undergo a redox reaction and result in production of MeHg (Parks et al., 2013). The formation of the MeHg is complex, as there are various components involved in its formation and transport, including the hydrology and soil (Figure 1). Hydrology is one of the main drivers for Hg and MeHg output in runoff (Krabbenhoft et al., 1995; Rudd, 1995; St. Louis et al., 1996; Bishop and Lee, 1997; Lee et al., 1998).

To battle the environmental Hg problems and protect human health related to consumption of freshwater fish, the World Health Organization (WHO) set an advisory fish consumption limit to 0.5 mg kg^{-1} wet weight (ww) on fish of 5 years old or 220 mm in length (Marusczak et al., 2011; WHO, 1990). The European Union Water Framework Directive has set Hg as a priority hazardous substance and European waters should have a good ecological and chemical status to protect ecological health (European Commission, 2000). Good ecological quality standards for mercury in fish should be 0.02 mg kg^{-1}ww, which all Member States should meet by 2020 (European Commission, 2008). However, there are high levels of Hg in Sweden and in the boreal regions of Scandinavia and North America (Johansson et al., 2001; Weech et al., 2004; Riva-Murray et al., 2011). Garcia and Carignan (2000) found that Hg levels were above the recommended WHO limits pre-harvest and post-harvest in fish. In North America, Kamman et al. (2004) found the highest mean Hg concentrations in pike (0.64 $\mu g * g^{-1}$) and white perch (0.72 $\mu g * g^{-1}$).

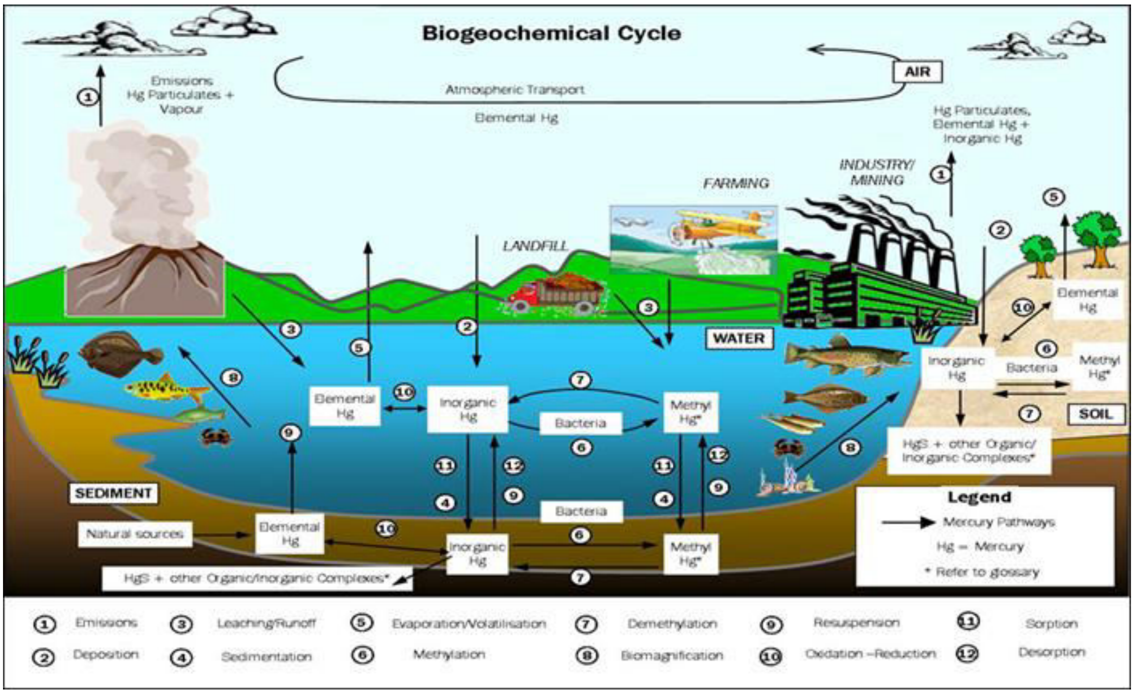

Figure 1. The Biogeochemical Hg Cycle, Ministry of the Environment, New Zealand 2014

1.4 *Mercury within the Forest Ecosystem*

Forests influence the freshwater ecosystems' response to Hg deposition overall and more specifically maintain the catchments' water quality (Johansson et al., 2001). Forests are major sinks of atmospheric Hg, so factors affecting the mobilization and methylation of Hg are important for Hg biogeochemical cycling. Atmospheric Hg accumulates in the tree canopies of these coniferous forests as dry deposition and is transported to the ground by litterfall (Lindberg et al., 1982; Zhang et al., 2009). Canopies serve as large Hg sinks, and dry deposition in forested areas can be higher than wet deposition because of the leaf surface area (Risch et al., 2012). Throughfall water, a means to rid excess water from leaves, is considered to be just as important as litterfall when evaluating total mercury (THg) input (Lee et al., 2000). Dry deposition occurs at a slower rate than wet deposition, therefore acts as an Hg filter to the surrounding catchment. Because the unstable form of elemental Hg is easily emitted back to the atmosphere, the Hg concentration changes in the soil and water of the forest catchments (Driscoll et al., 2013). In a catchment area, bioaccumulation of Hg in streams correlates to tree cover and wetlands (Riva-Murray et al., 2011; St. Louis et al., 1994; Rypel et al., 2008; Scudder et al., 2009; Ward et al., 2010).

The wetlands become wetter due to the forestry effect and have increased levels of Hg. This occurs because in Sweden forest soils are typically podzol and defined by low pH and high organic matter content. In the discharge zones of the boreal forests, much of the soil is comprised of peat, which are also hot spots of Hg methylation (Burns et al., 2014). The formation of MeHg occurs rapidly in wetlands, even within days as seen by Branfireun et al. (2005). Flooding of peat soils accounted for more than 97% of MeHg in the reservoir released from terrestrial land (St. Louis et al., 2004). Catchments with wetlands contribute more to the water Hg content than catchments without wetlands (Rudd, 1995; St. Louis et al., 1994a).

When there is an increase in forestry, there is an increase in [Hg] in runoff (Porvari et al., 2003).

1.5 *Scope of Research*

The aim of this project is to investigate Hg concentration in European perch (*Perca fluviatilis*) in 6 Swedish lakes before and after clear-cutting within the lake catchments. The sites were carefully selected based on substantial clear-cut information reported by Skogsstyrelsen, the Swedish Forestry Agency. The lakes are located throughout the country of Sweden from north to south. The fish sampling took place between the years 2010-2013. The hypothesis is there will be increased fish mercury in relation to size and age in perch post-harvest. Because the ecosystem is complex, other influencing factors must be considered (like growth rate), and not just before and after clear-cutting. When there is an increase in fish size, there is typically an increase in [Hg]. An analysis of covariance (ANCOVA) model will be used to take these factors into consideration. A secondary hypothesis is that there will be a decreased growth rate in the fish post-harvest. The hypothesis was tested by analyzing fish muscle for total Hg concentration, identifying the age of the fish, measuring fish weight and length, and taking the catchment characteristics from sampled water into consideration.

2. Materials and Methods

2.1 *Study Lakes*

Six Swedish lakes scheduled for intense clear-cutting in their catchments were carefully selected throughout Sweden (Figure 2). The lakes were small and isolated from other rivers and lakes. The lakes were easily accessible and fed into a larger catchment in the surrounding region. Information on planned forestry operations catchments is provided by the Swedish Forestry Agency Skogsstyrelsen (http://www.skogsstyrelsen.se/Aga-och-bruka/Skogsbruk/Karttjanster/Skogens-Kalla/). Skogsstyrelsen provides free GIS shapefiles of the planned clear-cut areas. One of the lakes, Svultentjärn, was scheduled to be cut, but never was. This lake served as a reference lake for the study. Various amounts of clear-cutting took place in 2012 in all of the lake catchments.

The catchment boundaries were manually drawn following the highest elevation points around the lakes (Appendix). This was not done by an automatic ArcGIS program function and therefore was subjective to my definition of a catchment boundary.

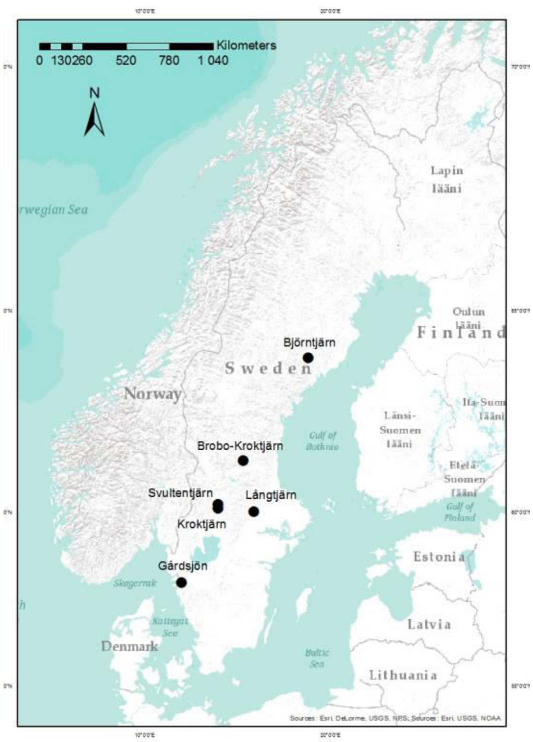

Figure 2. The study lakes are located throughout the country of Sweden, dominated by clear-cut areas.

2.2 *Fish Sampling and Preparation*

Fish were collected by net fishing (survey nets from www.lundgrensfiske.com) with 2 nets in each lake overnight during the sampling period. Each lake was sampled at least once before and after clear-cutting. European perch (*Perca fluviatilis*) were collected in the selected lakes in 2010, 2011 and 2013 during August. In addition to the six lakes, Gårdsjön was sampled both in the fall and spring in various years. Within 12 hours, the nets were rinsed and perch were stored in individual plastic bags. Length (L) and weight (W) of each fish were recorded. Whole fish were frozen (-20°C) and stored for further preparation at the lab.

In the lab, fish muscle samples were taken from the dorsal muscle and sectioned into plastic vials. Samples were freeze-dried (72 hours) and stored in the freezer for future Hg analysis. The weight of the fish samples was recorded before and after freeze-drying in order to determine the moisture content. The operculum were cut off the fish and stored in a freezer (-20°C) and saved for fish age analysis.

2.3 *Hg Analysis*

Total Hg concentration was analyzed on the freeze-dried muscle tissue using the SMS 100 Hg Analyzer (PerkinElmer, USA). The sample boats, forceps, and scoopula were cleaned using ethanol and deionized water to remove Hg residues before being baked in an oven (900°C for 3 hours) after they had been used for analysis.

The amount of muscle tissue used for Hg analysis was approximately 0.005-0.010 g. The instructions were followed as listed in the Hg analyzer manual (Perkin Elmer Operator´s Manual, N930-9098, Waltham, MA, USA) and according to US EPA method 7473. The samples were dried (100 secs. at 300°C) and decomposed (180 secs. at 700°C). Blanks and standards of certified reference material (fish proteins DOLT-4 ([Hg]= 2.58 ± 0.22 mg kg^{-1}) and DORM-4 (([Hg]= 0.410 ± 0.055 mg kg^{-1})) were run frequently (every 10 samples). Replicates were included once every 10 samples.

2.4 *Age Analysis*

Twenty perch were selected randomly from each lake sample for age analysis. Samples from lake Kroktjärn only contained 14 perch after clear-cutting. Only a sub-set of all fish from the lakes were analyzed for age. Fish selection for age analysis was done to cover a broad range of fish sizes. Before age determination the operculum were placed in a beaker of water, which was then heated around 150-200°C and mixed for approximately 2 minutes. After the heating procedure, the operculum were dried and the remaining skin was removed from the operculum. Age rings of the operculum were inspected underneath a stereoscope. If a fish seemed to be between 0-1 years old, then an age of 0 was given.

2.5 *Water Chemistry*

Water samples from each lake before and after harvest were analyzed by the Chemistry Department at the Swedish University of Agricultural Sciences for pH, total nitrogen (totN), total phosphorus (totP), iron (Fe), and total organic carbon (TOC). The department’s analysis used certified practices and analytical methods accredited by the Swedish Board for Accreditation/Conformity Assessment (SWEDAC).

2.6 *Statistical Analysis*

All statistical analyses were done in R 3.0.2 for Windows (R Foundation for Statistical Computing Platform). The standard deviation (SD), standard error (SE), and mean of the samples from the Hg analysis were calculated. When looking at the quantile-quantile (qq) plot for the raw data, the data were not normally distributed. To solve this problem, all data (except age) were logarithmically transformed. Scatter plots were created based on length, weight, Hg concentration, and age for each individual lake before and after clear-cutting. The log transformed data were visually inspected for normal distribution using a qq plot. In addition, 3 outliers from lakes Kroktjärn and Björntjärn that did not fit the regression model were excluded from further statistical analysis. An additional scatterplot was created comparing the spring and fall fish from the second Gårdsjön fishing data to determine any seasonal differences. A paired t-test for growth rate was done on all the fish samples.

To test the effect from forestry on fish Hg concentrations, the analysis of covariance (ANCOVA) was used. Like the analysis of variance (ANOVA), ANCOVA assumes normality, homogeneity of variance, and random independent samples. An ANCOVA model was done on all data using log (Hg) as the response and Before/After CC (clear-cut), Lake Name, log (length), log (weight), and age of the fish as treatment factors. To account for variance in fish Hg concentration that arises from differences in fish size, fish length, weight, and age were used as covariates in three separate ANCOVA models. The following expression was used in the ANCOVA:

$$log[Hg]=Int+a*CC+b*B+c*BK+d*G+e*K+f*L+Covar[(logL/logW/Age)]+Error$$

The letters represent the response of Hg to indicator variables to identify lakes (b-f) and clear-cut (a). Data from before the clear-cut was given an indicator value of 0 and the after clear-cut was given an indicator value of 1. The expression also includes covariates of log length, log weight, and age. Three separate ANCOVA models were calculated using covariates for length, weight, and age. The % change was calculated based on the reverse log of the [Hg]. The expression below illustrates how the calculations were determined:

$$\%CC=HgCC_{final}/HgCC_{no\ clear\text{-}cut}$$

The reverse log was taken for the regression coefficient before and after clear-cut. Once both numbers were determined for all three models, they were put into a ratio.

3. Results

3.1 *Catchment and Lake Water*

The studied lakes are overall small in size with a median water surface area of 5.62 (min~max: 3.78~31.33) with Gårdsjön being the largest one and Svultentjärn the smallest (Table 1). The median % clear-cut of the catchment was 28% (6~40). Svultentjärn was excluded in the median calculation. The largest clear-cut area was Långtjärn with 40% followed by Kroktjärn (36%). Aside from Svultentjärn, which did not experience a clear-cut, Gårdsjön had 6% of a clear-cut (Table 1). The median catchment area was 187.66 ha (95.43~236.29).

The lakes were found all throughout Sweden. The median latitudinal position was 60°1'N (58°3'~63°54'). Björntjärn was the northernmost lake at 63°54'N. Gårdsjön was the southernmost lake found at 58°3'N (Table 2). The other lakes were located in the middle region of Sweden (Table 2). The median longitudinal position was 14°E (12°1'~18°49').

The median pH post-harvest was 6.57 (5.79~7.24). The clear-cut catchments, excluding Björntjärn, increased in pH (Table 2). The pH of Svultentjärn remained the same at 5.79. Of all the clear-cut sites, Långtjärn had the lowest pH. The median Fe was 300 µg/l (19~550). Björntjärn had the highest Fe concentration at 470 µg/l. The median total P post-harvest was 7 µg/l (3~11). The median total N after clear-cutting was 242.5 µg/l (218~295). Långtjärn had the maximum total N and P concentration after clear-cut (Table 2). The median TOC post-harvest was 8.25 µg/l (5.0~10.2). Långtjärn and Kroktjärn had the highest TOC concentrations at 10.2 mg/l and 9.2 mg/l, respectively. Paired t-tests water chemistry concentrations did not indicate any significant differences in each analyzed water chemistry variable before and after CC (Table 3).

Table 1. Specific lake parameters used to determine clear-cut, including latitude, longitude, lake area, catchment boundary, clear-cut area, and % clear-cut.

Lake Name	Latitude	Longitude	Lake Area (ha)	Catchment Boundary (ha)	Clear-cut Area (ha)	% Clear-cut
Brobo-Kroktjärn	N 61° 22'	E 15° 20'	10.93	153.96	19.35	13
Kroktjärn	N 60° 7'	E 13° 58'	4.77	199.87	72.72	36
Långtjärn	N 60° 1'	E 15° 52'	6.46	236.29	93.87	40
Svultentjärn	N 60° 12'	E 13° 58'	3.78	95.43	0.0	0
Gårdsjön	N 58° 3'	E 12° 1'	31.33	179.96	11.89	6
Björntjärn	N 63° 54′	E 18° 49′	3.87	195.36	55.26	28

Table 2. Lake specific water chemistry (pH, total P, total N, and TOC) before and after clear-cutting.

Lake Name	Forest Harvest	pH	Fe (µg/l)	Total P (µg/l)	Total N (µg/l)	TOC (mg/l)
Brobo-Kroktjärn	Before	6.73	71	10	236	5.5
	After	7.06	76	7	263	6.2
Kroktjärn	Before	6.37	320	5	254	8.3
	After	6.57	300	5	238	9.2
Långtjärn	Before	5.51	400	16	477	14.8
	After	5.82	300	11	295	10.2
Svultentjärn	Before	5.79	860	10	277	8.2
	After	5.79	550	7	218	8.3
Gårdsjön	Before	7.07	40	2	259	5.4
	After	7.24	19	3	236	5.0
Björntjärn	Before	6.66	330	6	226	7.1
	After	6.57	470	7	247	8.2

Table 3. Paired t-test results for water chemistry variables (Table 2).

Factor	t	df	P value	Mean of the differences
pH	-2.237	5	0.075	-0.15
TOC	0.419	5	0.693	0.37
total N	1.231	5	0.273	38.67
total P	1.464	5	0.203	1.50
Fe	0.839	5	0.440	51.00

3.2 *Fish Age and Size*

Overall, the mean age of the fish was 3 to 5 years old. The mean lengths varied from 11.0 cm to 18.6 cm. The mean weights varied substantially between years from 17.83 g to 79.59 g. A significant positive correlation between weight (Figure 4) and length to [Hg] ($p<0.0001$) was found for the entire dataset (Figure 3). As the weight of the fish increased, there was a significant increase in the [Hg] ($p<0.0001$) (Figure 4). The bioaccumulation of Hg in the smallest fish seemed to vary compared to the larger fish in the sample size. A significant positive correlation also exists between age and [Hg] (Figure 5). The same observation is evident in the youngest fish having less of a correlation, particularly in the fish less than 1 year old. In the oldest fish, there is a plateau in the bioaccumulation of Hg.

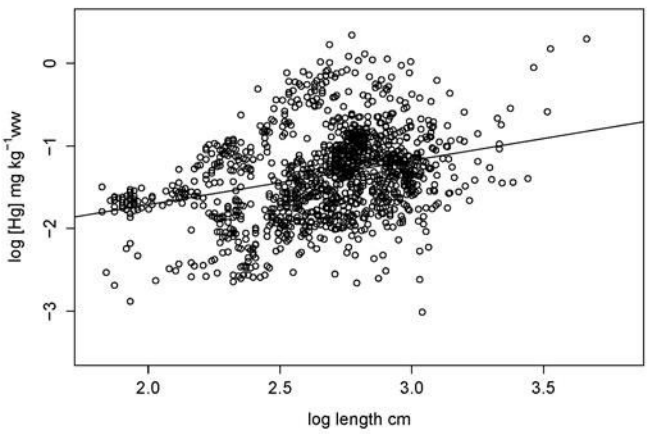

Figure 3. Regression plot of the relation between length and fish [Hg].

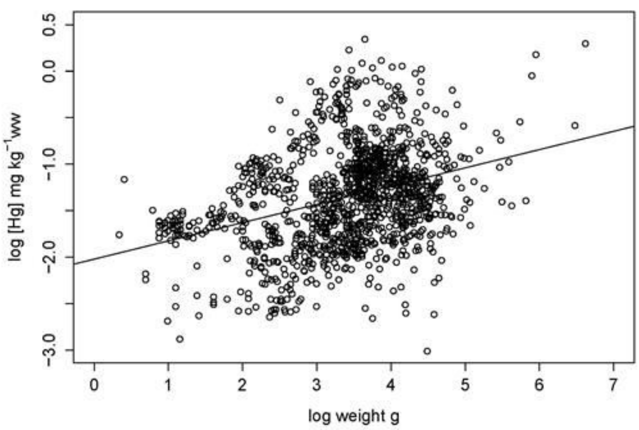

Figure 4. Regression plot of the relation between weight and fish [Hg].

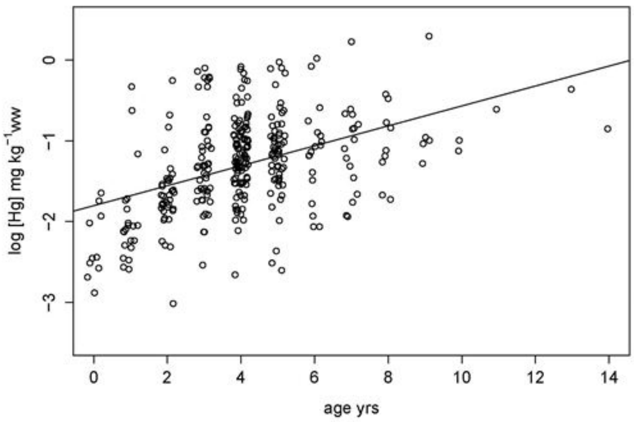

Figure 5. Regression plot of the relation between age and fish [Hg].

3.3 *Mercury in Fish*

There were differences between the lake perch [Hg] before clear-cutting (Table 4). Kroktjärn had the highest [Hg] (0.450 mg kg^{-1}) and Brobo-Kroktjärn had the lowest [Hg] (0.207 mg kg^{-1}). The [Hg] of Svultentjärn, the reference lake, was 0.207 mg kg^{-1}, while the [Hg] pre-harvest was 0.243 mg kg^{-1}.

The highest mean [Hg] was found in Lake Kroktjärn, with almost a doubling in concentration compared to the before clear-cutting data (0.840 mg kg $^{-1}$) (Table 4). The mean perch [Hg] for Långtjärn increased from 0.229 to 0.475 mg kg $^{-1}$ after CC. The mean [Hg] in Kroktjärn was much higher than the mean [Hg] of Brobo-Kroktjärn (Figure 6). Långtjärn, Kroktjärn, and Brobo-Kroktjärn were also higher in Hg content than the reference lake Svultentjärn. For instance, Kroktjärn's fish Hg increased drastically after clear-cut. There was also an increase for the mean values of Gårdsjön from 0.261 to 0.272 mg kg $^{-1}$ (Figure 6). Svultentjärn decreased from 0.270 to 0.266 mg kg $^{-1}$.

Table 4. Fish characteristics (number of perch, mean age, mean length, mean weight, growth rate, and mean Hg) before and after clear-cutting.

Lake Name	Forest Harvest	Number of Perch (N)	Mean Age ±Mean SD (yrs)	Mean Length ±Mean SD (cm)	Mean Weight ±Mean SD (g)	Slope of Growth Rate ± SE (cm/yr)	Mean Hg Wet Weight ±Mean SD (mg kg $^{-1}$)
Brobo-Kroktjärn	Before	89	4 ± 2.70	18.5 ± 2.70	70.31 ± 24.35	0.057 ± 0.011	0.207 ± 0.071
	After	165	4 ± 2.83	17.5 ± 3.75	58.21 ± 38.05	0.020 ± 0.004	0.306 ± 1.008
Kroktjärn	Before	168	3 ± 1.10	11.3 ± 2.90	17.83 ± 15.05	0.061 ± 0.009	0.450 ± 0.246
	After	14	3 ± 1.56	14.0 ± 0.83	29.71 ± 5.82	0.012 ± 0.003	0.840 ± 0.150
Långtjärn	Before	79	4 ± 1.60	11.0 ± 5.30	25.00 ± 44.8	0.038 ± 0.007	0.229 ± 0.167
	After	29	4 ± 2.72	17.4 ± 6.28	79.59 ± 146.16	0.043 ± 0.008	0.475 ± 0.304
Svultentjärn	Before	263	4 ± 1.60	14.8 ± 2.70	36.20 ± 17.8	0.042 ± 0.004	0.270 ± 0.099
	After	52	5 ± 2.85	14.1 ± 8.82	30.90 ± 16.84	0.021 ± 0.003	0.266 ± 0.120
Gårdsjön	Before	188	3 ± 3.60	16.1 ± 4.40	57.65 ± 65.42	0.065 ± 0.005	0.261 ± 0.165
	After	43	5 ± 3.61	18.6 ± 5.04	76.84 ± 55.79	0.041 ± 0.005	0.272 ± 0.120
Gårdsjön 2*		40	3 ± 2.03	15.7 ± 4.39	49.18 ± 50.63	0.021 ± 0.007	0.274 ± 0.140
Björntjärn	Before	21	4 ± 1.15	15.5 ± 2.00	36.71 ± 11.81	0.047 ± 0.005	0.350 ± 0.096
	After	123	4 ± 1.84	14.4 ± 1.95	28.51 ± 9.06	0.013 ± 0.006	0.317 ± 0.130

*This lake was fished independently by another researcher during the fall and spring seasons. The data includes different years in which they were fished. The data is only used to see seasonal differences.

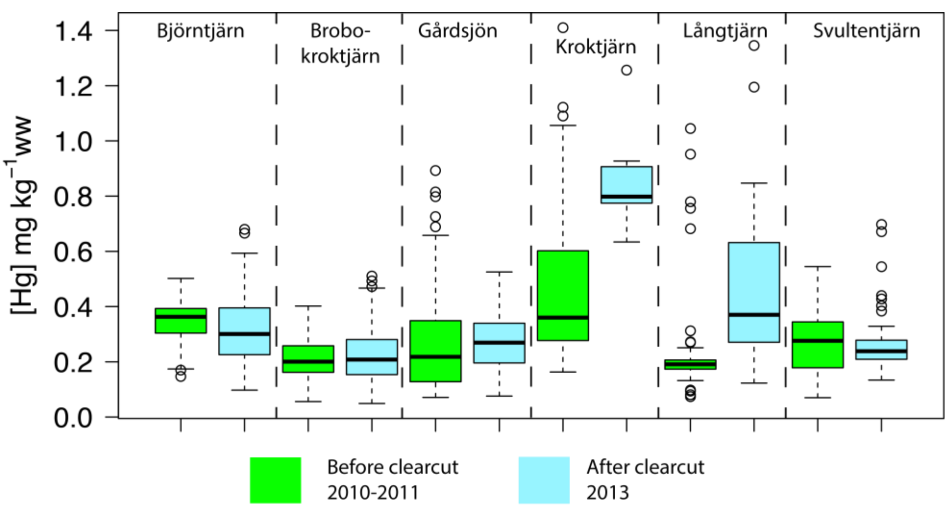

Figure 6. Box and whisker plot of the [Hg] before and after clear-cut in all of the study lakes. Svultentjärn was not clear-cut.

3.4 *ANCOVA*

The ANCOVA showed an overall significant increase in [Hg] from all lakes after clear-cutting in all three models, including length (R^2=0.52, p<0.0001, N=1240), weight (R^2=0.49, p<0.0001, N=1240), and age (R^2=0.52, p<0.0001, N=340) (Table 5). Although the model using age was a subset of the original data, it too showed an overall significant increase in [Hg] (R^2=0.55, p<0.0001, N=320). Correlation coefficients indicated an increase in fish [Hg] by 9%, 10%, and 15% after clear-cutting using length, weight, and age as covariate, respectively (Table 5).

Table 5. **ANCOVA results with regression coefficients for clear-cut (CC) and lakes Björntjärn (B), Brobo-Kroktjärn (BK), Gårdsjön (G), Kroktjärn (K), and Långtjärn (L) as indicator variables, and covariates (length, weight, and age of fish).**

	Regression Coefficient	± Standard Error		p Value		
ANCOVA variable	L	W	A	L	W	A
Intercepts	-4.32 ± 0.11	-2.75 ± 0.05	-1.70 ± 0.06	0.0001	0.0001	0.0001
a (CC)	0.09 ± 0.03	0.10 ± 0.03	0.15 ± 0.05	0.0014	0.0014	0.0023
b (B)	0.11 ± 0.04	0.15 ± 0.04	-0.05 ± 0.08	0.0086	0.0086	0.5157
c (BK)	-0.45 ± 0.04	-0.46 ± 0.03	-0.66 ± 0.09	0.001	0.001	0.0001
d (G)	-.024 ± 0.03	-0.26 ± 0.03	-0.26 ± 0.06	0.001	0.001	0.0001
e (K)	0.81 ± 0.04	0.81 ± 0.04	0.88 ± 0.09	0.001	0.001	0.0001
f (L)	0.21 ± 0.04	0.26 ± 0.04	-0.29 ± 0.08	0.001	0.001	0.0005
Covar	1.10 ± 0.04	0.40 ± 0.01	0.12 ± 0.01	0.0001	0.001	0.0001

3.5 *Fish Growth Rate*

Fish growth rate were significantly different (t=3.6, df=5, p<0.015) in lakes after clear-cut compared to before clear-cut. Although there were not sufficient age samples after clear-cutting, the growth rate was already showing signs of slowing. Gårdsjön, for example, exhibited a significant negative correlation between age and fish size. From the regression plots before clear-cutting, there was a steep incline in the slope of the growth rate (Figure 7).

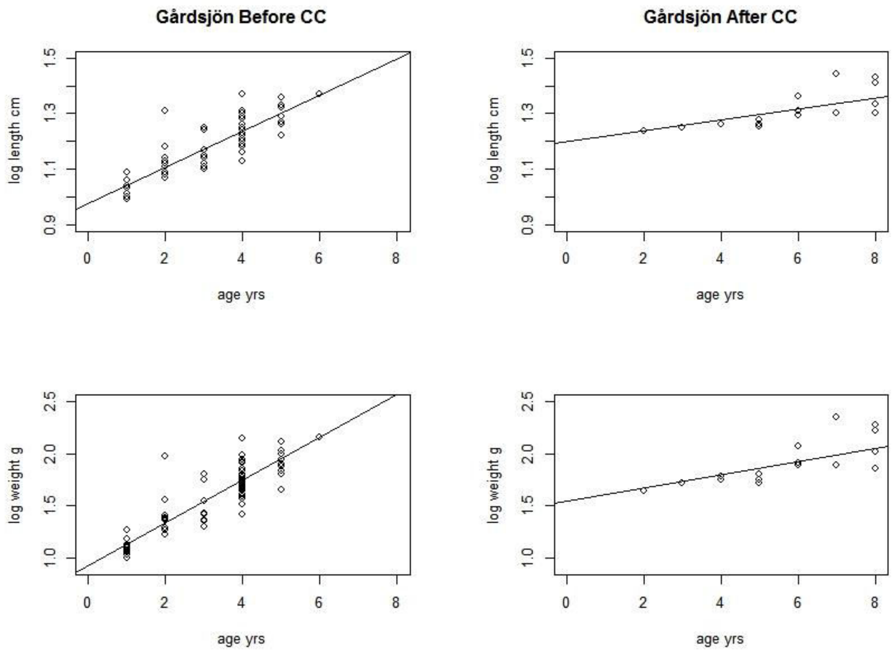

Figure 7. Regression plots of growth rate (in terms of length and weight) in Gårdsjön before and after clear-cutting.

3.6 *Seasonality in Gårdsjön*

Samples obtained for Gårdsjön showed a significant positive correlation between length and Hg concentration for fish Hg data collected during fall ($p<0.00$, $R^2=0.82$) (Figure 8). Comparable size data collected during spring showed and a significant negative correlation to Hg concentration ($p<0.003$, $R^2=0.69$) (Figure 8).

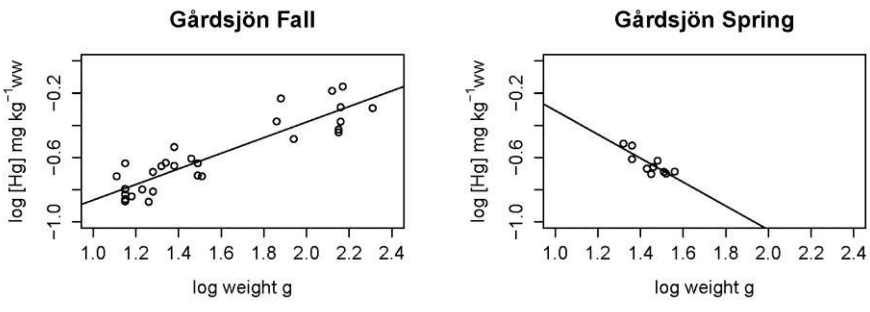

Figure 8. Regression plots of relationship between size and [Hg] for spring and fall in Gårdsjön.

4. Discussion

4.1 *Mercury and Forestry*

Bishop et al. (2009) predicted an increase in Hg levels in fish due to complete catchment harvesting would be between 10 to 25%. The six lakes presented in this thesis had an elevated Hg concentration after the first year of clear-cutting of approximately 10% with approximately 20% of the catchment harvested. The previous predictions on Hg in fish after forest harvest are alarmingly evident in these small catchments. Garcia and Carignan (2000) found Hg concentrations in fish were significantly related to the ratio of clear-cut areas in Canada. These are consistent with the current study because the highest clear-cut areas also had the highest increases in mean [Hg]. For instance, Långtjärn has one of the highest clear-cut areas and highest increase in mean [Hg], and Gårdsjön has one of the lowest clear-cut areas and lowest mean change [Hg]. When there was more clear-cut in the catchment, the direct result was the increased mobilization of Hg because the hydrology changed due to an increase in DOC transport and the lack of evapotranspiration in the trees. Mitchell et al. (2012) found that Hg pools on the forest floor post-harvest may lead to bioaccumulation in aquatic biota, which corroborated the initial hypothesis of our study. A similar study by Skyllberg et al. (2009) found a significant increase in MeHg runoff from young spruce forests in the highest postglacial coastline 0-4 years after harvesting, which further supports that forestry practices affect Hg bioaccumulation within the ecosystem. There was no increase below the highest shoreline, indicating that the [Hg] accumulation is a complex process and dependent on several parameters in the catchment, one of which is clear-cut.

A study conducted in Canada found an increase in zooplankton abundance after harvesting took place (Prepas et al., 2001). To what degree zooplankton are affected by [Hg] is unclear, but Hg does bioaccumulate within these organisms (Garcia and Carignan, 1999; Foster et al., 2012). There is a missing link in the relationship between the zooplankton and [Hg] levels in fish. This study relates to our results because it shows clear-cutting plays an important role in controlling Hg bioaccumulation in biota in the catchment.

4.2 *Watershed Characteristics*

Garcia and Carignan et al. (2004) found that when comparing Hg levels among the different lakes, one should consider trophic level and watershed characteristics. One of the characteristics to consider is the topography of the catchment (Appendix). Typically, more elevated areas will have an increased runoff amount. Hilliness is not the primary cause of increased runoff of MeHg. Even if the environment is flat, the forest harvest will have a larger effect on the MeHg runoff (Smerdon et al., 2009). Our study was supported by Mitchell et al. (2007), where Hg was highest in hilly areas surrounding peatlands, where it was more susceptible to runoff. Riva-Murray et al. (2011) found that topography plays a critical part in MeHg and DOC levels, specifically the distance from topographic depressions and riparian wetlands. The catchment of Kroktjärn had a high proportion of wetlands coupled with the hilly terrain. This characteristic in the catchment could be one reason why Kroktjärn also had one of the highest TOC levels among the studied lakes.

4.3 *Hg Bioaccumulation Correlates to Fish Size*

All the ANCOVA models showed significant differences in size to total Hg. In all cases, the variables' regression coefficients increased, but the length model gave the best prediction of the fish size to Hg relationship (R^2=0.49). Weech et al. (2004) found that northern pikeminnow Hg concentration could be predicted based on the fork length. Pikeminnow, similar to perch, are used as indicators for predicting Hg levels in water. Age was a main factor for determining Hg concentration in rainbow trout (Weech et al., 2004). In our study, there were 3 fish from each model (<10 cm) that exhibited high levels of Hg and did not fit the regression model. It was also determined that the fish were under 1 year old due to no definitive growth ring on the operculum. This seems to be common in fish because biodilution of Hg can occur when there is an increase in growth rate (Weech et al., 2004; Stafford and Haines, 2004). It is plausible that these smaller fish were growing slower and thus accumulating equal amounts of Hg to the older fish.

4.4 *Growth Rate and Hg*

Freshwater fish are not only affected by bioaccumulation of Hg, but the toxic substance also plays a role in their growth rate. The effects of growth rate were seen before and after the clear-cutting in our study. Simoneau et al. (2005) found that growth rates were significantly related to Hg levels in walleye. For instance, slower growing fish would have higher levels of Hg compared to faster growing fish (Wang, W.-X., 2012). Another study found growth rates in walleye and pike correlated with Hg levels, and could be used to predict Hg levels in fish (Lavigne et al., 2011). In the United States, a significant relationship was found between growth rate and Hg concentrations in bass and crappie (Sacket et al., 2009). Lepak et al. (2013) found that Hg concentrations influenced growth rates in rainbow trout and walleye, and they can be used in Hg prediction modeling for freshwater fish. A study on walleye also found a significant decrease in growth related to Hg concentration. Simoneau et al. (2005) determined that growth rates could account for differences in Hg concentrations in the populations of fish. Simoneau et al. (2005) states that faster growing fish have less Hg concentrations than slower growing fish. These types of results correlate with our findings because the growth rates were different after clear-cut and could possibly be related to the Hg concentration in the fish.

4.5 *Seasonal Variation in Fish Hg*

The additional data from Gårdsjön shows that seasonality plays a part on this lake. Similar results were found in a study where Hg concentration in zooplankton was lowest in the spring (Garcia et al., 2007). Because a perch's diet consists of zooplankton, this study supports that perch would have a lower Hg concentration in the spring, thus the bioaccumulation would be lower. Another reason for the seasonal shift is that perch have different feeding habits during the year. Although feeding habits of perch can be misleading as the stomachs contain only recently eaten material, they can provide hints into the Hg concentrations found in the muscle tissue. A study done on feeding habits of yellow perch by Wilkens et al. (2002) found that their stomach contents were a combination of macroinvertebrates and plant material in the fall season, and chironomids/amphipods between

October and June. This would further explain why Hg concentrations of the perch were higher during the fall season. For instance, perch rarely eat other perch, but if not enough zooplankton is available they could become more predatory (Wilkens et al., 2002). Two of the fish from our sampling were caught with another perch in their mouths. Once the fish had digested the other, the Hg levels would be much more elevated in the predatory perch because it would accumulate any remains from the fish it ate. Generally, the larger perch grow, the more piscivorous they will become (Jacobsen et al., 2002).

4.6 *Other Influences on Fish Hg Concentration*

Clear-cutting is not the only factor that determines the bioaccumulation of Hg. For instance, DOC serve as vectors for THg and MeHg, and are correlated to levels of Hg in the catchment. Clayden et al. (2013) found that pH promotes Hg bioavailability, which provides the sulfur-reducing bacteria to perform methylation in the water column. Långtjärn exhibited the highest clear-cut and highest Hg concentrations, but also had the highest TOC concentrations of 10.2 mg/l. This accounts for the amount of carbon in the water. Elevated organic carbon levels correlate with higher Hg levels because there is increased methylated Hg when it is bound to organic matter (Garcia and Carignan, 2004). The differences in fish Hg concentration before and after clear-cut could not be explained by any effect in the water chemistry since it did not change pre- and post-harvest period.

5. Conclusions and Recommendations

This study focused on the role forest harvesting plays on bioaccumulation of Hg in perch in Swedish lakes. Based on the results of the present study, we can give one piece of evidence that clear-cutting does impact Hg levels in perch in Swedish lakes. Previous studies conducted on fish in Canada found similar results, although few studies have been done on fish Hg levels in recent years. One study predicted there would be higher levels of Hg in perch after harvest and further tests should be done. Our thesis research was the first project conducted in any Nordic country looking at Hg bioaccumulation in perch post-harvest. This ground-breaking discovery could change how forestry practices are done in the future to protect our ecosystem. In addition, the study is significantly sound, and can support many of the other studies currently available.

The study incorporated an ANCOVA model which accounted for the variation in length, weight, and age in the fish. Although the ANCOVA model showed an overall increase in Hg in fish from all the lakes, the test does not take into consideration the variation of water temperature, water chemistry, and percentage of clear-cut from each specific lake. Because these lakes are polyhumic with no clear water lakes, it is harder to see TOC effects play a role. The variation among the lakes, however, could further explain the different amounts of Hg found.

Only one reference lake was used as a control in the study. To improve the accuracy of the results, more reference lakes should be chosen in addition to selecting larger monitored lakes. It would be interesting to see the comparison with different lake sizes.

Only a subset of fish was age analyzed and therefore we cannot make certain that the growth rate regression results give significant findings. By doing further age analysis on all fish, the accuracy of the growth rate estimations would increase. To see any seasonality among the fish in spring and fall, only the same size fish should be compared.

Microbial processes in the lakes are important when considering lake characteristics because the rate of methylation would differ. Bacteria and soil samples were not obtained during the field work. In future research, this information should be collected and documented because much of the origin of MeHg relies on the sulfur and iron reducing bacteria found in the lakes or in the wetlands. Although literature suggests the [Hg] are higher in the water, soil, organic matter, and fish, there is still little known about the exact path the MeHg takes when formed by the bacteria and introduced into the fish. Studies differ greatly on Hg bioaccumulation in zooplankton. Stable nitrogen isotopes will aide us in determining the fish diet and trophic level. Thus one of our next steps is having the nitrogen isotope analysis of samples done. Lastly, knowing the total area of the wetlands within the catchment boundaries could aide in further explanation of the results due to their humic characteristics. This area of research should be further investigated to better understand the food web of the fish.

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8. Appendix

8.1 Legend for Lake Catchment Boundaries After Clear-cutting.

8.2 Topographic Map of Brobo-Kroktjärn’s Catchment After Clear-cutting.

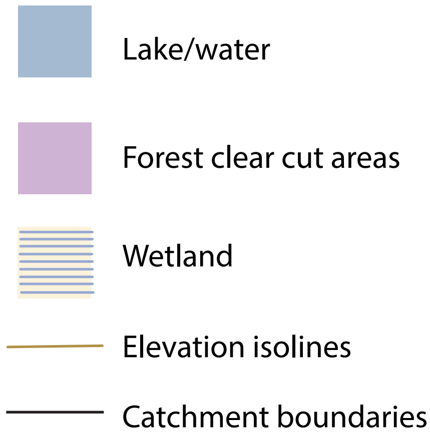
8.3 Topographic Map of Kroktjärn’s Catchment After Clear-cutting.

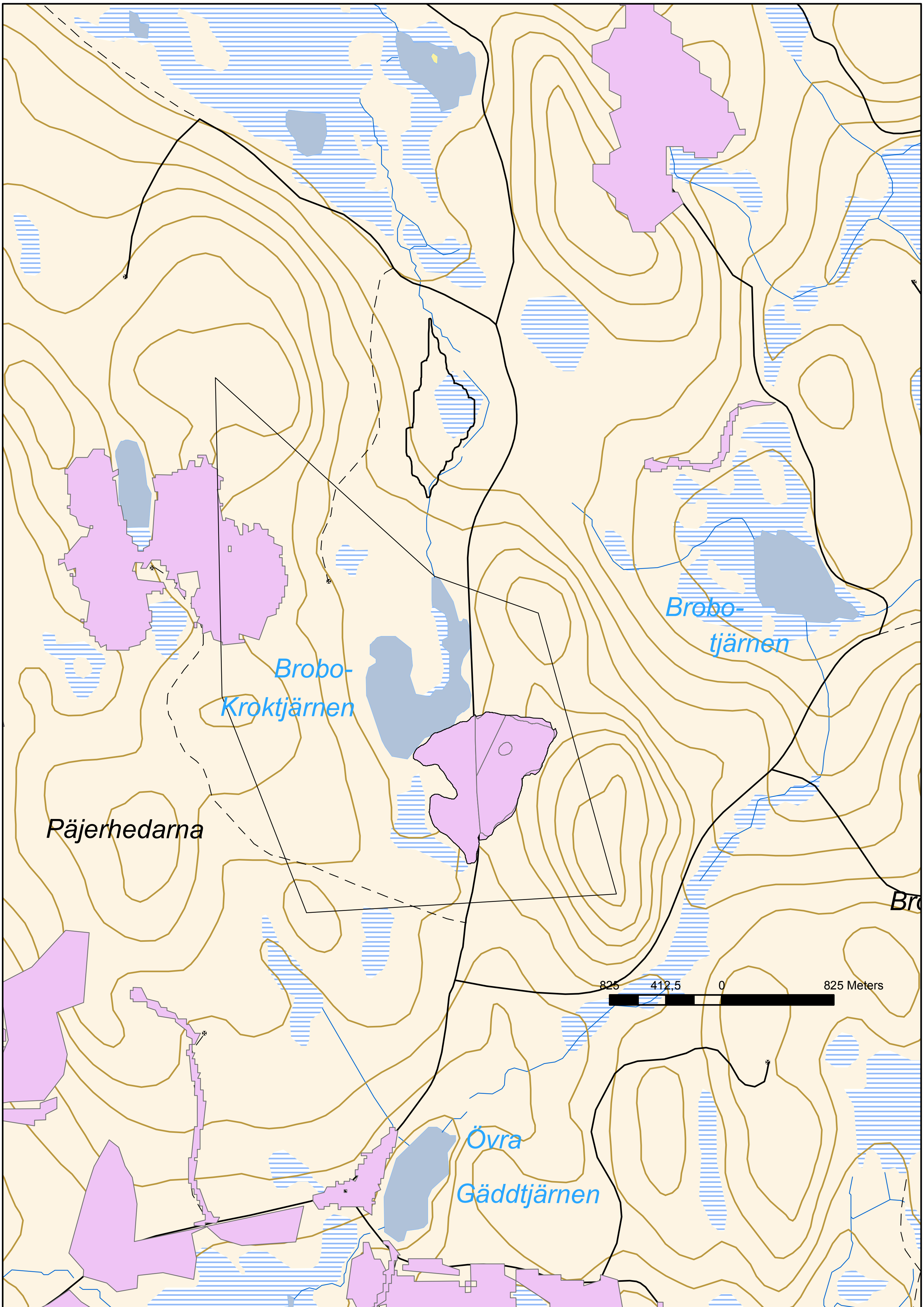
8.4 Topographic Map of Långtjärn’s Catchment After Clear-cutting.

8.5 Topographic Map of Svultentjärn’s Catchment After Clear-cutting.

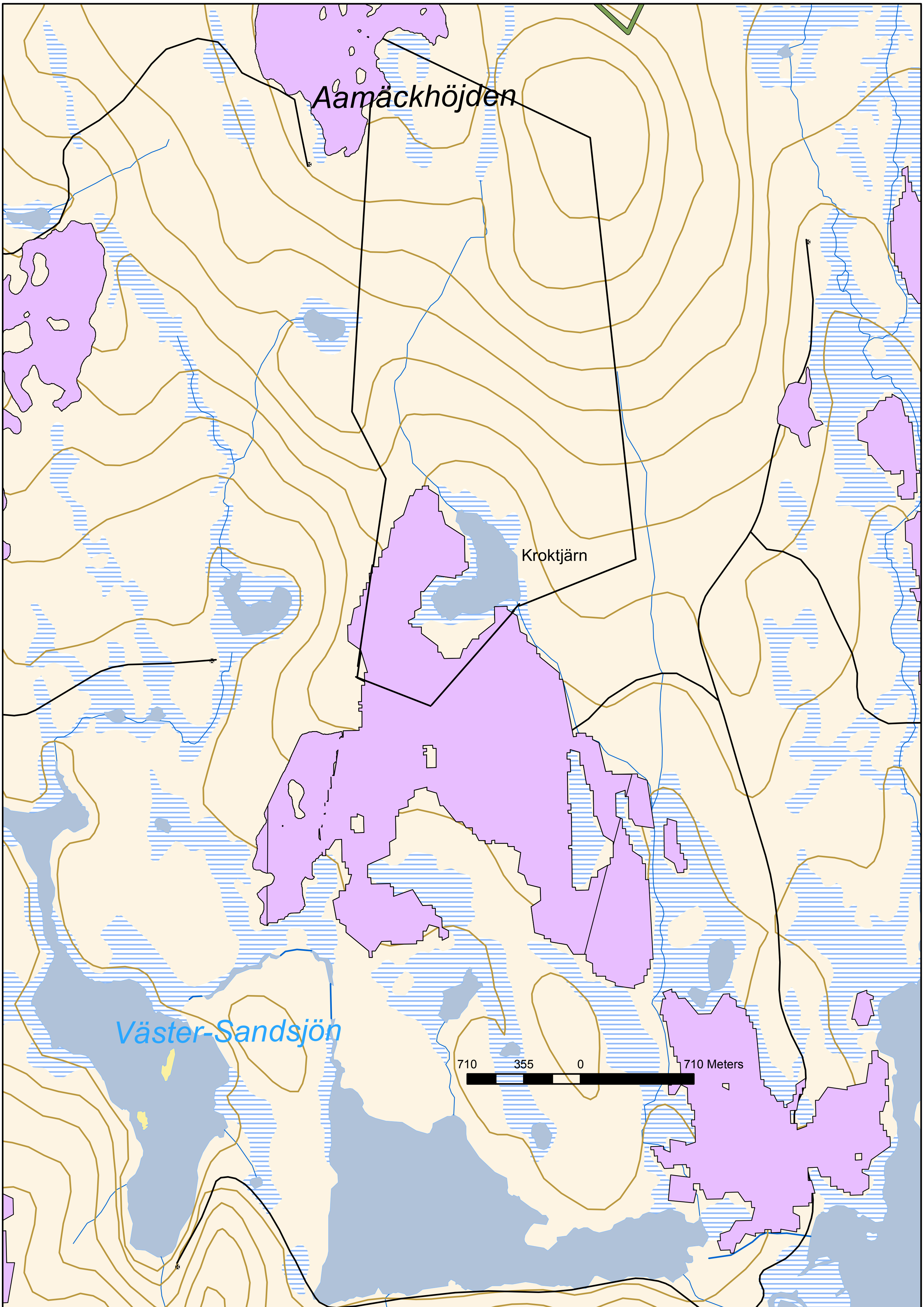
8.6 Topographic Map of Gårdsjön’s Catchment After Clear-cutting.

8.7 Topographic Map of Björntjärn’s Catchment After Clear-cutting.

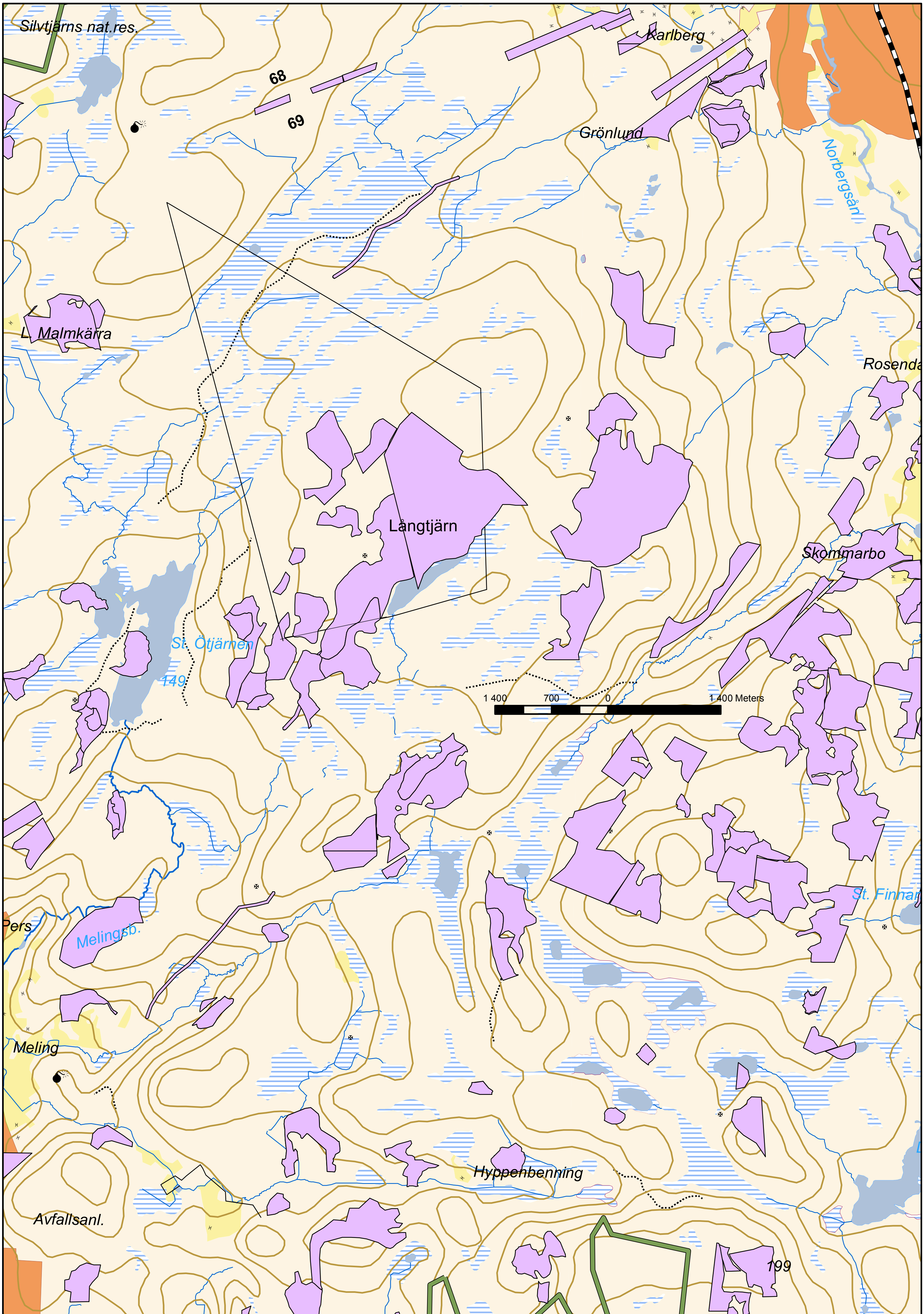

Lake/water
Forest clear cut areas
Wetland
Elevation isolines
Catchment boundaries



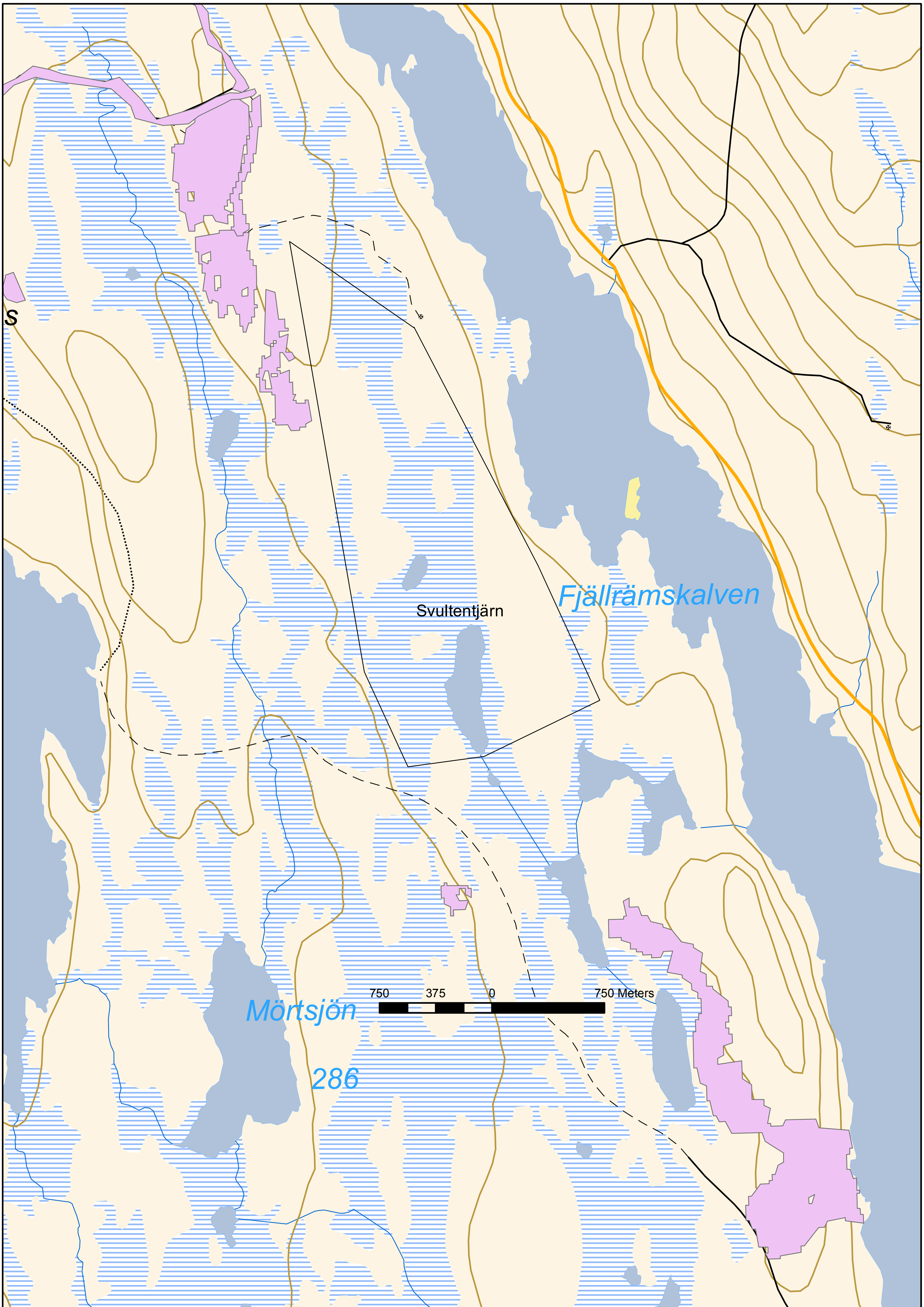
Brobo-
Kroktjärnen
Brobo-
tjärnen
Päjerhedarna
Bro
Övra
Gäddtjärnen
825
412,5
0
825 Meters

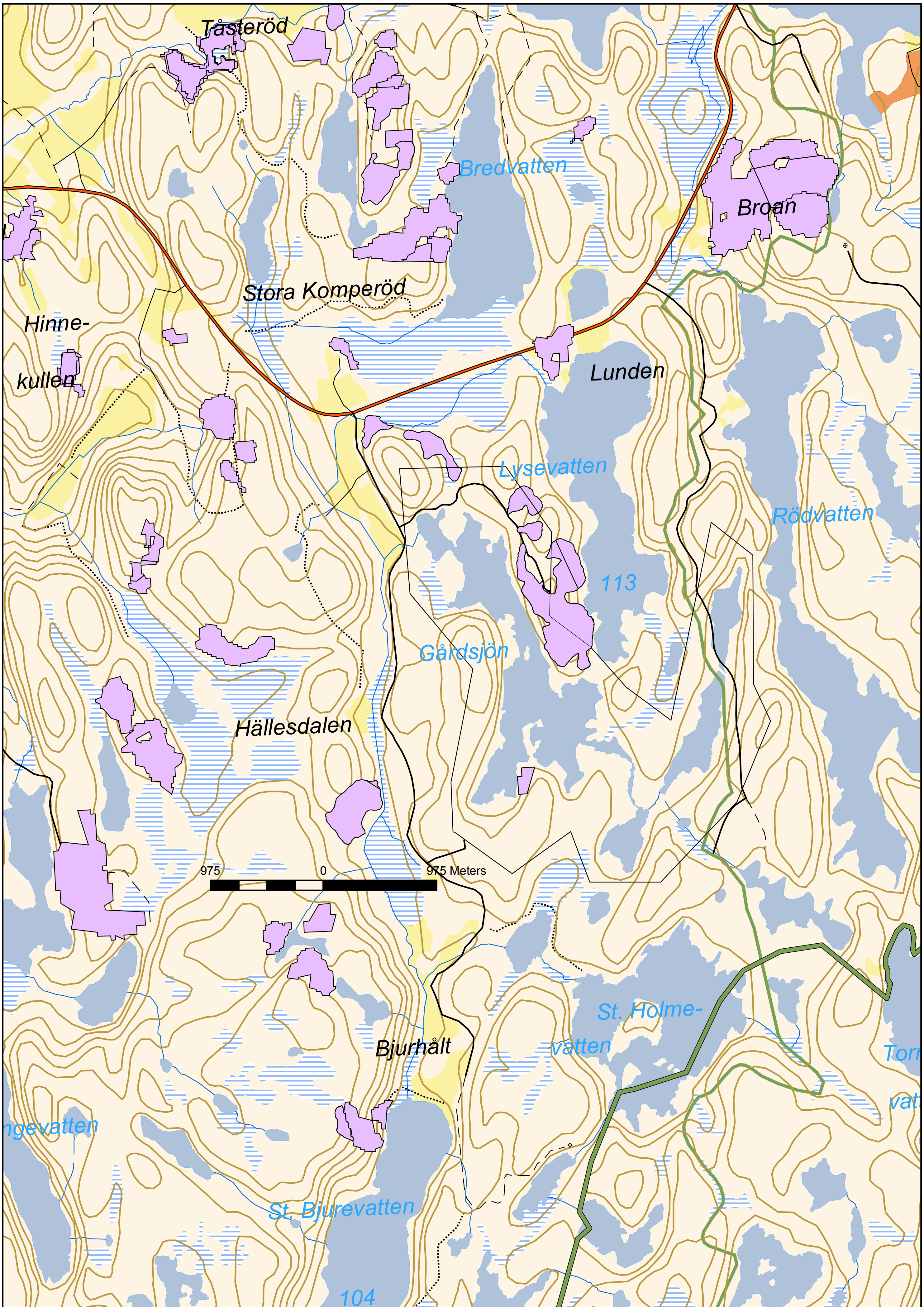


Aamäckhöjden
Kroktjärn
Väster-Sandsjön
710
355
0
710 Meters



Silvtjärns nat.res.
68
69
Karlberg
Grönlund
Norbergsån
L. Malmkärra
Rosenda
Långtjärn
Skommarbo
St. Ötjärnen
149
1 400
700
0
1 400 Meters
St. Finna
Pers
Melingsb.
Meling
Hyppenbenning
Avfallsanl.
199


S
Svultentjärn
Fjällrämskalven
Mörtsjön
286
750 375 0 750 Meters


Tåsteröd
Bredvatten
Broan
Stora Komperöd
Hinne-
kullen
Lunden
Lysevatten
Rödvatten
113
Gårdsjön
Hällesdalen
975
0
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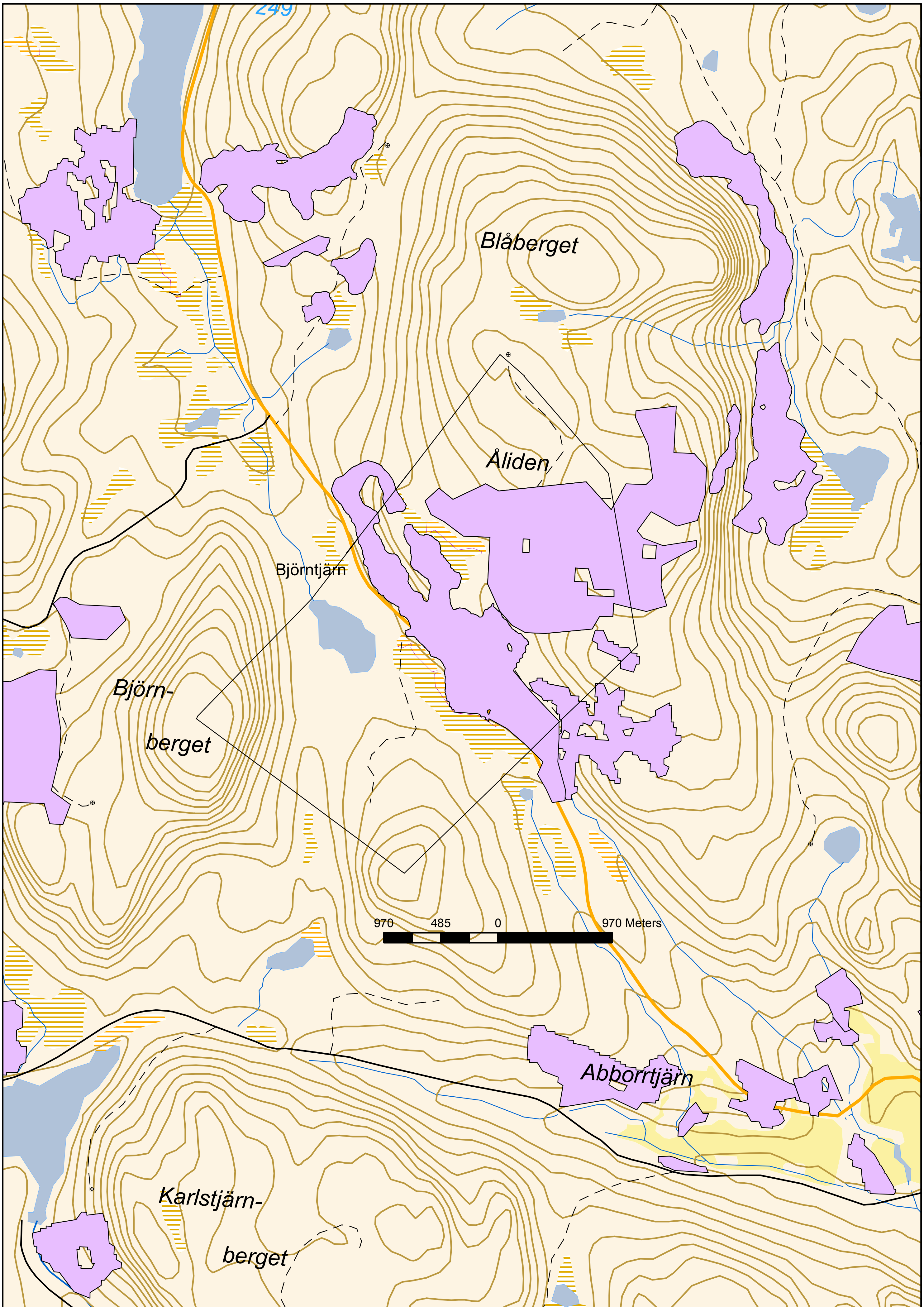
St. Holme-
vatten
Bjurhålt
ngevatten
St. Bjurevatten
104


249
Blåberget
Åliden
Björntjärn
Björn-
berget
970
485
0
970 Meters
Abborrtjärn
Karlstjärn-
berget