Effects of fish farming on phytoplankton in northern lakes

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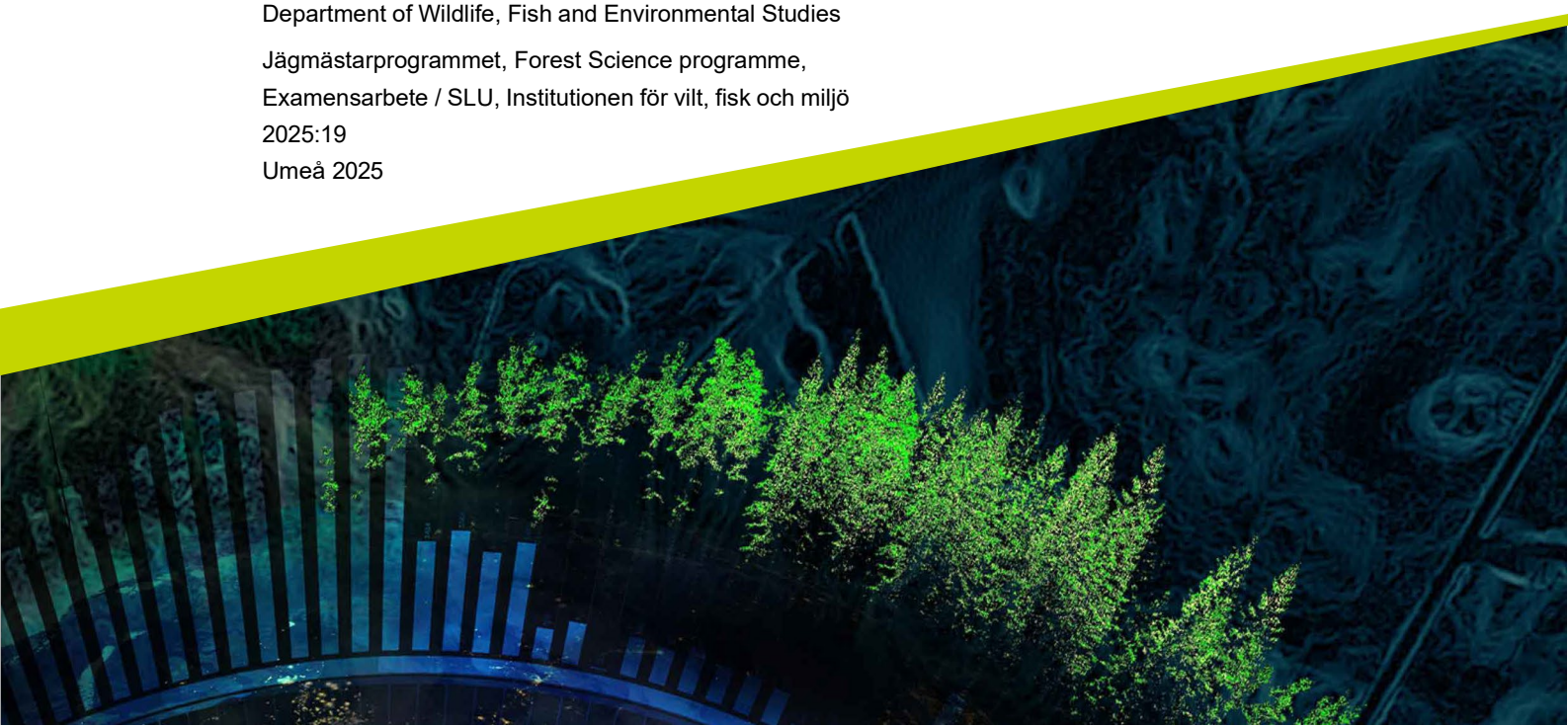

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Abstract

During the last years, fish farming in Sweden has increased drastically as a result of a growing interest in locally farmed food. As of today, the environmental consequences of fish farms with open cages is not well studied. In this study, we aim to analyze the effects of open cage fish farming on plankton production in nutrient poor, northern lakes (lake Storuman and lake Hornavan). We hypothesize that nutrient leackage through fish farming activities will cause a gradient in nutrients downstream from the fish farm. We also hypothesize that an increased nutrient concentration at the fish farm will cause an increase in primary production in the lake and that experimental nutrient additions close to the fish farm will not increase primary production due to nutrient limitation relief for plankton. Primary production was measured in the lakes through incubation of water together with nutrient additions (N or P) at 0.10m depth and we sampled water for NO3, NH3 and phosphorus in a transect downstream from the fish farm. We then compared our data together with national monitoring data of both chemistry and plankton biomass for the two lakes to visualize and analyze a longer time period with the plankton biomass aiding in the analysis of primary production that we sampled. While primary production tended to be higher in Storuman compared to Hornavan (average 14 Mmol vs 10 Mmol, peak 36 Mmol vs 14 Mmol) this was not statistically significant. The highest measured primary production was observed in the upstream location of Storuman (mean = 25 µ Mmol·L^{-1}) compared to the other sample points. Combining the national monitoring data for water chemistry with our own, we observed higher mean values for ammonium and phosphate in lake Storuman compared to Hornavan. For our measured transect, we observed a significant linear decrease for ammonium and a small linear increase for nitrate based on distance downstream from the fish farm. No such trend was observed for phosphate. We compared algal biomass in Storuman and Hornavan using the national monitoring data comparing with research. Storuman had an average of 1854 µg L^{-1} while Hornavan had 91 µg L^{-1}. This suggests that Storuman have increased algal growth due to the fish farm. The resulting water chemistry analysis suggests that ammonium concentrations close to the fish farm are significantly elevated compared to other parts of the lake. Despite us not finding a significant effect of primary production on location, the results from the primary production together with the algae concentrations suggest tendencies for elevated primary production in the lake. Lake Storuman does show elevated nutrient levels, but not across the whole lake. Algae concentrations close to the fish farm are relieved of their nutrient deficiencies since incubated bottles displayed no increases in primary production at this particular location. Management decisions have to take into account the risk of eutrophication when operating fish farms in nutrient deficient waters.

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Abbreviations

Abbreviation	Description
C	Carbon
DIN	Dissolved inorganic nitrogen
DOC	Dissolved organic carbon
DPM	Disintegrations per minute
GPP	Gross primary production
N	Nitrogen
P	Phosphorous
PAR	Photosynthetically active radiation
PP	Primary production
TDP	Total dissolved phosphorous

1. Introduction

Fish farms in Sweden have a long history that goes all the way back to the 1600:s, and by the 1800:s and forward the interest of producing farmed fish was increasing, even to the point of export to other countries (Paisley et al. 2010). Fish farming with open cages is a relatively cost- and climate effective food resource, most of their environmental impact is caused by nutrient leackage and organic matter in the form of metabolites (Eriksson et al. 2017). The main cost-reducing effects are the lesser need for farming equipment compared to other measures, such as land-based systems which is a more costly method (Eriksson et al. 2017). These land-based systems often require treatment of outgoing water as well as large energy requirements. Open cages are used due to the high water exchange requirements of salmonid species, and recreating these conditions in artificial environments would be costly because of both the high energy costs and the large water exchange. Today, most fish farms are in hydropower dam reservoirs (Kiessling & Futter 2023). This is because these are already anthropologically modified systems (Kiessling & Hansen 2024).

As of year 2023, the production of farmed fish increased by 5% compared to the previous year, measured as stocking fish and food fish (Leonardsson 2024). Rainbrow trout (*Oncorhynchus mykiss*) constitutes about 87% of the total farmed fish for food, followed by arctic char (*Salvelinus alpinus*) , eel and others such as salmon and brown trout (*Salmo trutta*). This, in total, amounted to approximately 10 900 tons of fish (Leonardsson 2024). The number of active fish farms for year 2023 was approximately 157. This includes fisheries for food fish, stocking fish, crayfish, stocking crayfish, mussles and oysters, with the largest amount of farms providing food fish and stocked fish (Leonardsson 2024). The amount of fish feed required to support fisheries vary based on the size of the fish farms. Vattudalens fisk AB, which runs the fish farm in Storuman, Västerbotten, have a yearly allowance of 2400 tons of fish feed at maximum production (Rebane 2023).

There is currently a growing interest for an expanded aquaculture to meet human food demand (Kiessling & Futter 2023). The environmental consequences are, however, not well known. There are arguments made for the possibility of increasing the lake productivity by slightly elevating the nutrient load of the lake through fish feed and excrements, primarily via phosphorous (Bristow et al. 2008). However, nutrient enrichment can also cause unwanted increases in algal production, especially in nutrient poor lake ecosystems (Rydberg et al. 2003; Rydin et al. 2008; Findlay et al. 2009; Paterson et al. 2010).

Open cage aquaculture is known to release considerable amounts of organic waste and inorganic nutrients during production (Wang et al. 2012; Redmond et al. 2024). Primarily, aquaculture releases carbon (C), nitrogen (N) and phosphorous (P). These compounds have the ability to affect parts of the ecosystem. Dissolved inorganic nutrients are known to promote growth for phytoplankton and benthic algae (Fork et al. 2020). Particularly in clear, oligotrophic lakes (Bergström et al. 2013). Plankton increases can affect energy transfer between autotrophs to consumers, thus altering the natural food web (Bergström et al. 2013) . Larger particles such as fish excrements and uneaten feed sink relatively quickly, with a possible accumulation in sediments as a result. Smaller particles remain in the water column and can be consumed directly by zooplankton and fish (Troell et al. 2009; Wang et al. 2012). Wang et al. (2012) found that approximately 70, 62 and 70% of total C, N and P from fish feed were lost to the environment in a salmonid farm in Norway. Folke et al. (1994) found that a fish farm, producing 100 tons of salmon, have nutrient releases on par with settlements of between 850 and 3200 people. At Lake Södra Bullaresjön, research found that approximately 9% of total organic and 9% of phosphorous deposition was caused by excrements from farmed fish (Johansson et al. 1998). Increasing nutrient release to lakes can lead to reduced water clarity dominated by plankton, i.e eutrophication. Oxygen levels may also be affected through plankton decomposition. This depletion in oxygen will be most prominent in the deeper water layers which can cause a release of phosphorous from sediments. The result can be a damaged ecosystem creating a feedback loop that sustains eutrophication (Hessen et al. 2024).

1.1 Purpose

The purpose of this study is to evaluate the impact of open cage fish farming on the production of plankton in a nutrient poor lake, in this case Lake Storuman, Sweden. I aim to investigate whether fish excrements and unconsumed fish feed alter the primary production (PP) and biomass of phytoplankton. This is done to address potential ecological consequences of nutrient enrichment from fish farms such as increased algal growth and changes in ecosystem dynamics.

1.2 Hypotheses

H1 An increasing nutrient leakage through fish excrements and unconsumed fish feed in Storuman fish farms will result in a decrease in nutrient concentrations along a transect downstream from the fish farm

H2: Increased nutrient concentration near the farm will cause increased primary production (PP) and plankton chl-a concentrations in the lake as compared to the control lake Hornavan.

H3: Increased nutrient concentration near the farm will relief plankton from nutrient limitation and therefore experimental nutrient additions will not increase PP close to the fish farm.

1.3 Study area

The study areas in question were lake Storuman (fish farm) and lake Hornavan as a reference lake, chosen because Hornavan doesn't have an active fish farm. Figure 1 show the coordinates for incubation (GPP) sampling and also for the water chemistry transect. Lake Storuman is located in Västerbotten county in Storuman municipality. It is a heavily modified water body with an area of 171 km2 and is a part of Umeälvens main catchment area. There are two active companies operating fish farms in Storuman. There are a total of three active farms, one smaller near the inlet of the lake, one in the middle and one near the outlet. In this study, we sampled the middle farm in Kaskeluokt. This farm was of main interest because we believe it is least affected by the other fish farms in the lake. Currently, the lake has an unsatisfactory ecological potential because of the presence of a hydropower dam and fails to reach a good chemical status due to high levels of mercury and polybrominated diphenyl ethers (PBDEs) (*VISS-Vatteninformationssystem Sverige* 2023a). Lake Hornavan has an area of 262 km2, and is located in Norrbotten county, Arjeplog municipality. It is also a heavily modified body of water (hydropower dam) with the same status as lake Storuman when it comes to the same factors regarding both ecological potential and chemical status (*VISS-Vatteninformationssystem Sverige* 2023b)

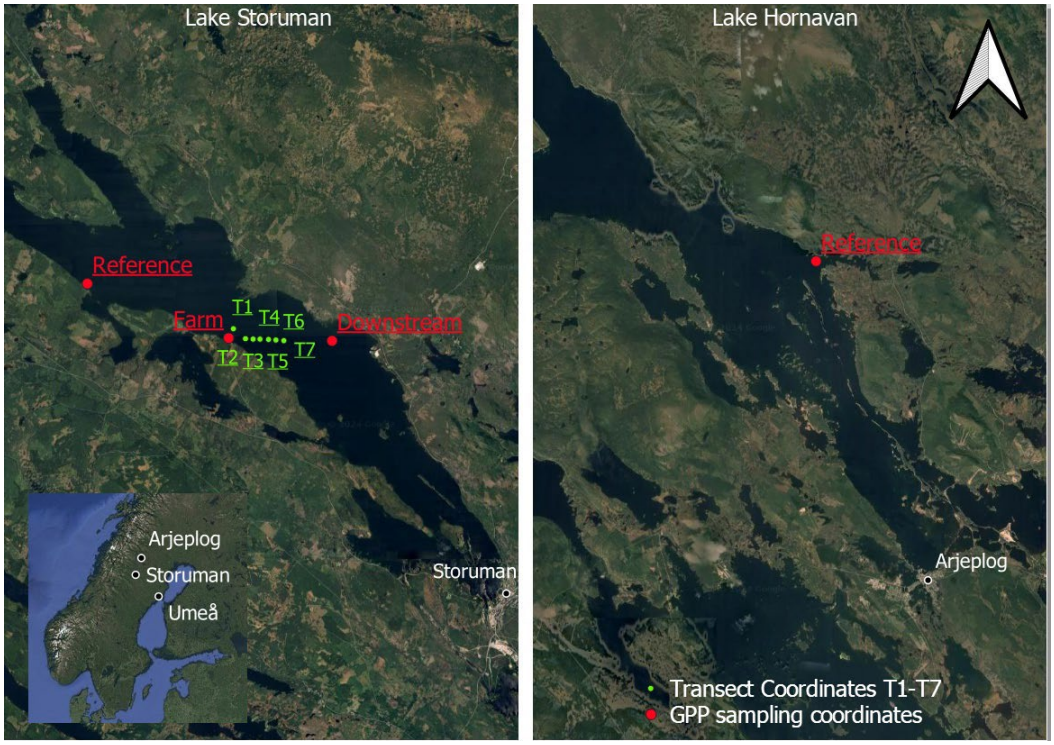

Figure 1. Map over lake Storuman and Lake hornavan with sample points. QGIS 3.10, 2024-11-28 A Coruña, incorporated Google satellite imagery via QuickMapServices plugin (Map data ©2024 Google

2. Method

For our research, we conducted a week of field studies in early September where we measured PP at different water depths (0m, 0,5m, 1m, 4m) and with different nutrient additions at 3 locations at lake Storuman, which contains a fish farm roughly in the middle of the lake. One of the locations was close to the fish farm, one was 5 km downstream from the farm and one location 10 km upstream of the farm considered as control. We used Hornavan as a separate control/reference lake which was sampled two weeks before. We also sampled water in bottles to look at the water chemistry composition, we primarily looked at ammonium (NH_4), nitrate as NO_2+NO_3 and phosphate (PO_4), but we also analyzed total dissolved phosphorous (TDP) and dissolved organic carbon (DOC). This was done to see whether the fish farm in particular contributes to nutrient leakage into the water. All samples were filtered (0.45 µm Millex HA filter; Millipore) and frozen before nutrient analysis. In total, n=18 samples were taken in Storuman of which n=7 samples were sampled as a transect downstream from the fish farm. From Hornavan, a total of n=3 samples were collected for water chemistry analysis.

2.1 Water chemistry analysis

The water samples were analysed for nutrients on a QuAAtro 39 (Seal Analytical). NO_2+NO_3 is analyzed after reagents + samples pass through a copperized cadmium (Cd) coil forming an azo dye [method: MT3B Q-126-12 Rev 1]. NH_4 is analyzed through the salicylate method [method: Q-033-04 Rev.8] and PO_4 is analyzed using the molybdenum blue method [method: MT3A Q-125-12 Rev 1]. Total dissolved phosphorous (TDP) was analyzing in the same way after undergoing an on-line digestion step (alkaline acidic persulfate method) at 110 ºC and 0.90 MPa [method: Q-115-10 Rev. 4]. DOC is analyzed with a Formacs HT-I (Scalar) after combustion (870 ºC) of acidic water samples. All water samples were analysed at Umeå University.

2.2 Primary production analysis

For the PP, water was sampled from the different depths and poured into their respective bottles. Nutrient additions consisting of N and P (100 µg/L and 10 µg/L respectively) were added to 30 bottles at 0.10m depth with 4 replicates for every location (including dark bottles) except for the upstream location at lake Storuman where we used n=3 replicates for both nutrient additions at 0.10m. Nitrogen was added by 100 µg/L and phosphorous by µg/L. We had no nutrient additions to bottles deeper than 0.10m. For the control, n=53 bottles were used

which includes all depths and all locations (Storuman and Hornavan combined). I used an isotopic, radioactive tracer, carbon-14, to estimate primary production. I used both transparent and dark bottles to account for respiration. 3 µL of ^{14}C was added to each bottle by pipetting. The vials were then connected to ropes of determined lengths based on water sampling depth for each vial. The ropes were finally connected to a float and submerged under water (Bergström et al. 2013).

The bottles were incubated in the lake at their respective depths and left there for approximately 4 hours, between 10am and 14pm. The bottles were then collected and stored in a cooling bag. On shore, we added 1mL of 1M HCl to each bottle to stop the incubation and remove any unused DIC, ensuring that only organic carbon assimilated during photosynthesis during incubation is measured. In the lab, we transferred 5mL of liquid from each bottle into 20mL scintillation vials. The samples were then aired for 24h to degas excess $^{14}CO_2$ from the water, formed when HCl was added. 15 mL of scintillation liquid (Optiphase hisafe 3) was then added to all of the vials which were then shaken. We then added the vials to a scintillation counter (Perkin Elmer Liquid Scintillation Analyzer Tri-Carb 2910 TR. Software Quanta Smart) that estimates the radioactivity of each sample, which took approximately 24 hours to analyse all samples (n=84). Blanks were used to account for any background radioactivity from the water and/or scintillation liquid.

Photosynthetically active radiation (PAR) was also measured at each site for the different depths using a Li-Cor quantum photometer (Li 25-A) specifically designed to measure PAR under water. The PAR reading device is submerged under water at the desired depths (0.10, 0.50, 1, 1.50, 2 and 4 meters) and a reading of PAR is displayed in µmol/m^2 and s.

2.3 Primary production calculations

PP was estimated as the rate of carbon production per liter of water during the course of one hour (Bergström et al. 2013). To do this, the disintegrations per minute (DPM, i.e. the activity) from the scintillation counter for all replicates was used. PP for each depth, nutrient treatment, location and lake was estimated by subtracting the dark bottles used from the light bottles. Where there were multiple replicates, the means of the light bottles were calculated first before subtraction of the dark bottle DPM. Replicates of light bottles that showed lower DPM than the dark bottles in the same category were considered flawed and therefore removed. 31 replicates had to be removed due to this issue out of a total of 83 replicates.

To estimate PP, a known concentration of ^{14}C is added to each incubated bottle as ^{14}C bicarbonate. Since natural DIC (primarily consisting of bicarbonate, carbonate

and carbon dioxide) in the water dilutes the addition of ^{14}C in each bottle and the likelihood of ^{14}C uptake per unit of carbon fixed is reduced, a known uptake ratio of DIC to ^{14}C (constant variable, "C") is used. For my calculations, the following formula was used to calculate PP per hour.

$$PPPP = \frac{(DDPPDD \times DDDDDD \times DD \times VVVVVVVVVVVV)}{(14_{CC}\ aaaaaaaaaaaaaaaa \times aaiiaaVViiaaaaaaVVii\ aaaaVVVV}$$

Where DPM is disintegrations per minute (calculated by removing values for dark bottles and replicates) , DIC is a predetermined mean value of DIC collected from n=135 subarctic lakes (mean = 1.70 mg/L) (Puts et al. 2022). The volume of the bottles is used to scale results by the sample volume (ml). C represents the correction factor used to correct for plankton favouring ^{12}C over ^{14}C (1.05). This correction takes into account how much DIC is incorporated into the phytoplankton. The added activity of ^{14}C was 74000000 dpm. The incubation time was 4 hours and finally, we multiply with 1000 to convert from µM to mM.

2.4 Environmental monitoring data analysis

Finally, I used environmental monitoring data of water chemistry and plankton biomass from both Storuman and Hornavan (Swedish University of Agricultural Sciences (SLU) 2024). The water chemistry data was added to my data to have a longer time record and the phytoplankton biomass data was used as a complement to my PP data. The main focus for the water chemistry data was to look at NH_4-N, NO_2+NO_3-N and PO_4-P. These were categorized as below or over 2m in depth, with only samples during autumn included, since we sampled in September. In total, we used n=89 datapoints from Hornavan (monitoring data) and n=28 datapoints from Storuman (monitoring data) combined with our own datapoints from Hornavan and Storuman which were n= 3 and n=18 sample points respectively. The monitoring data are from 2006 to 2022. For plankton biomass, we summarized all algal species sampled to an average biomass, comparing Hornavan with Storuman. In total, we had n=4 datapoints from Hornavan and n=8 datapoints from Storuman (Miljödata-MVM. 2024). For the analysis of plankton, water samples are carefully shaken to get an even mix of the sample. The sample is then placed in a sedimentation chamber with a volume matching that of the lake type in question, meaning that it is based on the expected volume of plankton that is usually found in the specific lake in question. Sedimentation occurs in the dark and the required time is based on the size of the sample, 2 hours is enough for a 2ml sample. After sedimentation, a microscope is used for analysis using between 100 and 1500 magnification range (Naturvårdsverket 2010).

2.5 Statistics

All statistical analyses and generated graphs were made using R. We utilized R to statistically test our primary production data, our measured chemistry data from the transect and we also generated our boxplot for the algae analysis (Version 4.1.2; R Core Team 2021)

To compare the means of primary production between the different locations (Upstream, Downstream, Farm and Hornavan) an ANOVA was used. Specifically, to see if there is a significant difference between the primary production at the different locations. This is done in an attempt to statistically visualize and confirm whether the locations, which represent areas with differences in environmental conditions (farm being a potential nutrient source) show significant differences in primary production. We were unable to statistically test the effect of nutrient additions due to low replication, however, individual results are presented in figure 2.

Further, for comparing algal biomass between Lake Storuman and Hornavan the choice of a t-test was considered, but with only four replicates from Hornavan, this was not possible. Instead, a boxplot visualization was used to compare the algae concentrations from Storuman and Hornavan with a collection of algal biomass measured in 135 northern lakes (Paltsev et al. 2024). The boxplots represent the distribution of the data between the compared lakes, this includes the median, quartiles, range as well as outliers in the data (figure 4).

The collected water chemistry data from the transect downstream from the fish farm was statistically analysed using a linear regression to see if there was a statistically significant linear relationship in the nutrient concentration with distance from the farm. Nutrient concentration (PO_4, NO_2+NO_3 and NH_4) was the dependent variable and distance (m) was the independent variable, results are visualised in figure 3 . The generated R2 values shows how much of the observed variation that can be explained by the distance from the fish farm. The rate of change (being the slope of the linear model) estimates how high (increase) or low (decrease) the nutrient concentrations changes along the measured transect.

3. Results

The resulting primary production (means of all depths, 0.10, 0.50, 1, 1.50 and 2 meters) can be seen in (Figure 2). Primary production tended to be higher in Storuman as compared to Hornavan, (average 14 Mmol vs 10 Mmol and peak 36 Mmol **vs** 14 Mmol respectively), yet this was not statistically significant (F-value = 0.34, p=0.80).We observed higher values for PP in all locations in Storuman except for the downstream location with added nutrients compared to Hornavan. The highest measured primary production was sampled in the Storuman upstream location with added nutrients (mean = 25 µ Mmol·L^{-1}, Stdev = 2.10 Mmol·L^{-1}). The primary production for the farm location was considerably lower than the upstream location when looking at the nutrient added incubations. The largest difference can be observed between the downstream incubation with nutrient addition and the upstream incubation with nutrient addition. The upstream incubation with nutrient addition was higher than the control, while the nutrient added incubation downstream was lower than the control, however we didn't statistically test this due to low replication.

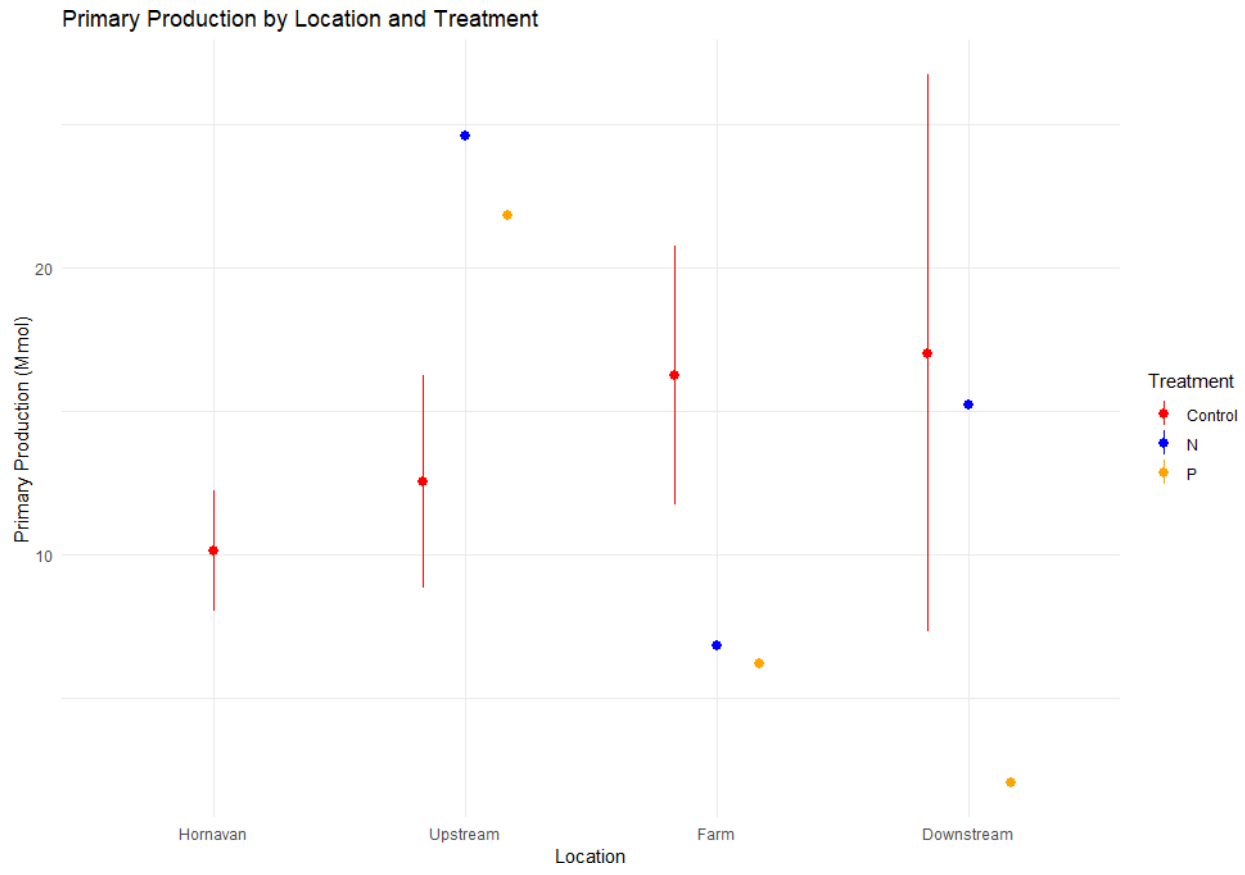

Figure 2. Scatter-plot with error bars showing mean primary production (y-axis) with standard deviation and with the tested locations on the x-axis.

National monitoring data combined with our own water sampling resulted in higher mean values for ammonium (NH_4) in Storuman , 26.50 µg L^{-1} with standard deviation of 22.01 µg L^{-1} (inside farm, <2m) compared to the control (Hornavan, <2m) We can also observe the same result for phosphate (PO_4-P), but the difference isn't as clear (table x). Nitrate displayed no such trends, here the control was higher (26.17 µg L^{-1}, Stdev 10.04 µg L^{-1}) than the samples from the farm (16.31 µg L^{-1}, Stdev 22.01, table x)

Table 1. National monitoring data combined with our sampled data, displayed as mean values for each depth category with standard deviations for each substance

Lake	Location	Depth	NH_4 (µg L^{-1})	NO_3+NO_2-N (µg L^{-1})	PO_4-P (µg L^{-1})	NH_4 Stdev (µg L^{-1})	NO_3 Stdev (µg L^{-1})	PO_4-P Stdev (µg L^{-1})
Hornavan	No farm	<2m	5.50	26.17	1.28	2.51	10.04	0.83
Hornavan	No farm	>2m	3.61	39.52	1.07	2.29	13.98	0.26
Storuman	Outside farm	<2m	8.47	19.86	1.63	6.18	8.41	0.91
Storuman	Inside farm	>2m	10.00	17.55	0.48	0.42	0.34	0.07
Storuman	Outside farm	>2m	6.65	19.73	0.85	2.36	2.36	0.62
Storuman	Inside farm	<2m	26.50	16.31	1.88	22.01	22.01	1.45

The water analysis of our sampled transect showed decreasing values for ammonium (NH_4). Nitrate (NO_2+NO_3) however, was increasing further downstream from the fish farm. Ammonium had a significant linear decrease based on distance downstream away from the fish farm ($R = 0.69$, $p = 0.02$ slope = -5.86). For nitrate, we observed a small, linear increase based on distance from the farm ($R = 0.69$, $p = 0.02$ slope = 0.67), while no such trend could be observed for phosphate ($R = 0.27$, $p = 0.23$, slope = -0.60, figure 3 and figure 3)

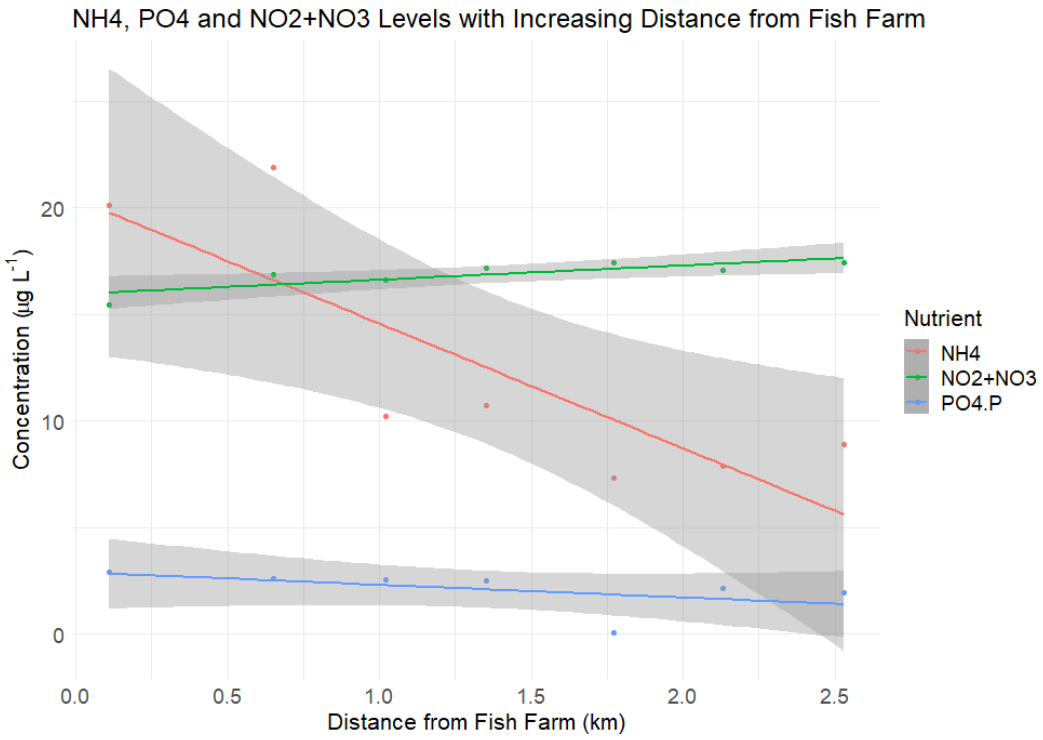

Figure 3. Measured transect data as seen visually with increasing distance away from the fish farm in Storuman

For the comparative analysis of the algal biomass between national monitoring data Miljödata-MVM (2024) (data collected between 2006 and 2012) and Paltsev et al (2024) we observed large values for Storuman (average = 1854 µg L^{-1}) compared to Hornavan (average = 91 µg L^{-1}) and Paltsev et al (2024), which was a collection of 135 lakes (average = 1292 µg L^{-1})

4. Discussion

Anthropologically altered waters that include fish farming run a risk of causing eutrophication (Peuhkuri 2002; Hessen et al. 2024) Research has shown that anthropological fragmentation of rivers caused by dams affect ecological processes negatively, as observed by Renöfält et al. (2010). In Storuman, we found highly elevated levels of algae concentrations (average = 1854 µg L^{-1}). As concluded by Paltsev et al. (2024), phosphorous has been recognized as the main limiting factor for phytoplankton growth, this includes southern Sweden as well which generally have higher concentrations of nutrients in the water (Ulén & Fölster 2007). If we look primarily at northern Sweden though, we find that primarily nitrogen is the limiting factor for lake productivity, but are in general, nutrient poor (Jansson et al. 2001; Lewis Jr 2011; Bergström et al. 2013, 2015). As observed by (Myrstener et al. 2022), nutrient limitation was primarily observed as primary N-limitation and secondary limitation of P. Through our measured transect, we could not see a significant linear effect of phosphorous increase along the gradient downstream from the fish farm.We did however find a statistically significant linear increase in nitrate and a decrease in ammonium in nutrient concentrations further downstream along our transect, which indicates that ammonium nutrient concentrations close to the fish farm are significantly elevated compared to other parts of the lake.We hypothesized (hypothesis 1) that all nutrient concentrations measured would be decreasing downstream, this was only found to be the case for ammonium in our measured transect. While other sources in the immediate vicinity of the lake might alter and affect nutrient composition on a small scale, such as logging or agricultural practices, they mostly affect small-scale streams near recent clearcuts or agricultural land. As observed by Löfgren et al. (2009), clearcutting increased concentrations of multiple compounds with ammonium amongst those measured in a small stream. For total lake concentrations however, we would not observe this type of increase in ammonium (a doubling from 9 ug/L to 20 ug/L) from forestry or agricultural practices (Klaus et al. 2018). This strongly suggests that the measured ammonium concentrations are a result of the cage aquaculture in the lake. Enrichment of either N or P will increase productivity in an ecosystem as observed by Elser et al. (2007), management decisions therefore need to take this into account when planning for expanded aquaculture or establishing aquaculture in previously untouched waters to mitigate uncontrolled nutrient enrichment.

Interestingly, we could not statistically show a significant effect for primary production on location in our ANOVA test despite observing much larger values in the raw data of primary production for most locations in Storuman compared to the control in Hornavan. This was likely due to few replicates, we had to remove

n=31 replicates that were considered flawed (since DPM for light bottles during incubation never should be lower than that of the dark bottles).The methodology is highly sensitive to differences in added ^{14}C. We hypothesized that we would observe higher primary production and plankton chl-a concentrations in the lake compared to the control, Hornavan. We could only observe higher values for the chl-a concentrations (figure 4), and not the primary production. Interestingly, there are very few studies that looked at a comparison in primary production between waters affected by aquaculture and those without, meaning there is room for improvement within this research.

Algae concentrations in Storuman are visibly one order of magnitude larger than those from Hornavan, meaning that lake Storuman show plankton biomass on par with the most productive lakes in Sweden. This is in line with Hypothesis 2 and supported by findings by Paterson et al. (2010) from Canadian as well as Swedish Paltsev et al. (2024) fish farming experiments. We can observe a large spread in values for Storuman compared to both Hornavan and the collection of northern lakes (figure 2) and this is in line with our primary production data that show large variation across the lake, with a tendency towards lower PP upstream from the farm, while PP near and downstream from the farm was higher. Even though a large number of replicates were flawed and we could not significantly observe a difference in primary production based on location. Comparing the algal data with the primary production, we observe tendencies for elevated primary production. This is because the farm location has been relieved of its nutrient limitation through fish excrements of which we cannot observe in the upstream location where primary production is lower and an addition of nitrogen elevates primary production values instead. Algal concentrations were measured to be around 200% larger in Storuman compared to the control in Hornavan.These findings are in line with hypothesis 3 and nutrient elevations through fish excrements was also observed by Johansson et al. (1998); Rydberg et al. (2003); Rydin et al. (2008); Findlay et al. (2009); Paterson et al. (2010).

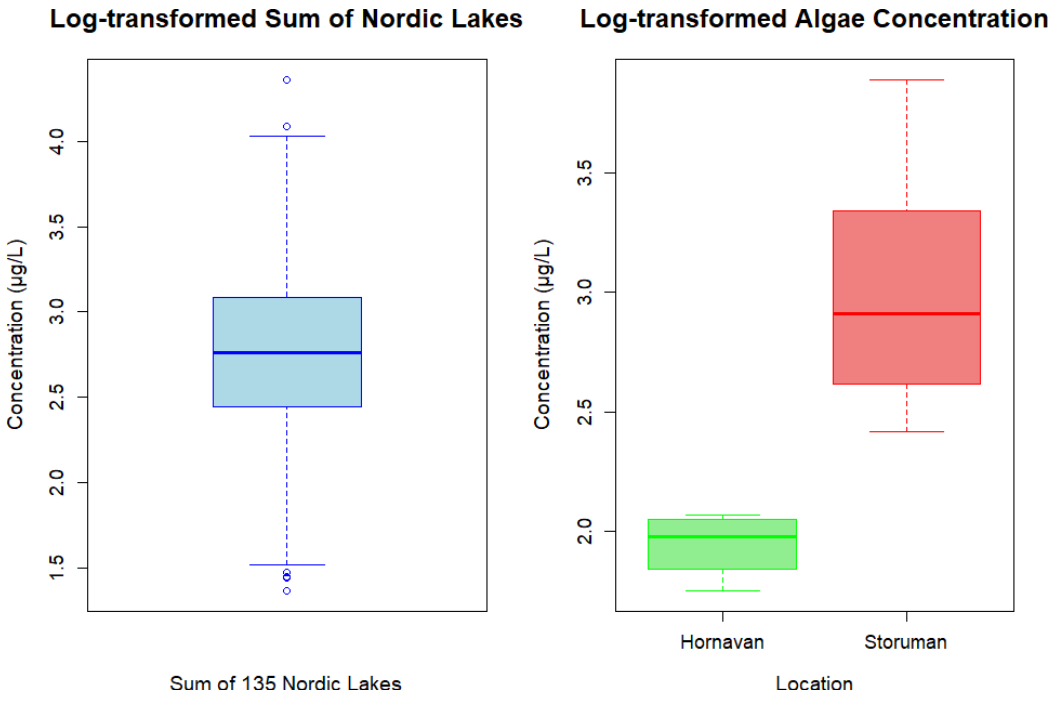

Figure 4. Boxplot of algae concentrations between our measured locations and compared with data from Paltsev et al. (2024).

5. Conclusion

Based on the evidence presented comparing Storuman to both the control and the lakes analyzed by Paltsev et al (2024), it is safe to acknowledge that Storuman show elevated nutrient levels in some locations, but not across the whole lake. This is highlighted by the high concentrations of algae measured together with the primary production data and the measured nutrient levels in the transect. Even though we didn't observe a significant correlation between primary production levels and location in the lake, based on the evidence, we can conclude that the lake does have elevated levels of primary production close to the farm in comparison to the upstream, downstream and Hornavan location. The results support our hypothesis of elevated primary production levels even though we could not statistically confirm it in this study. It is however clear that the algae close to the fish farm are relieved of their nutrient deficiencies since the incubated bottles with added nutrients close to the farm had little to no effect on the measured primary production. This was indicated by a satiated nutrient availability to the algae close to the farm as opposed to the upstream location, where nutrient added incubations increased the measured primary production compared to the control. It is safe to say that more research on aquaculture affected waters is required. Primarily looking at before and after effects of long-term aquaculture and the resulting ecosystem impact, especially in waters with historically low anthropogenic effects.

6. Acknowledgements

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Popular science summary

With an increased interest in locally farmed food, fish farming in Sweden has increased in the last few years. The impact on the local environment however, is not well known. In this study, we want to investigate the effects of open cage fish farming on plankton production in northern lakes (lake Storuman and lake Hornavan). We believe that nutrient leakage through fish farming activities will show as a decrease in nutrients downstream from the fish farm. We also believe that increasing nutrient concentrations near the fish farm will increase primary production in the lake as a whole. Through nutrient relief close to the fish farm, we believe that we will not observe an increase in primary production in the vicinity of, and inside the fish farm. We measured primary production through incubating bottles of lake water at different depths with added nutrients (N or P) at a depth of 0.10m. Looking at the water chemistry in the lake, we sampled water in a transect downstream from the fish farm and then compared our findings with national monitoring data of both water chemistry and plankton biomass for both lakes. We found primary production to be higher in Storuman compared to Hornavan (average 14 Mmol vs 10 Mmol, peak 36 Mmol vs 14 Mmol) but it was not statistically significant based on sample location. We observed our largest values for primary production in the upstream sample location at Storuman (mean = 25 µ Mmol·L) compared to all other sample locations. When combining our findings with national monitoring data, we observed higher mean values for ammonium and phosphate in Storuman compared to Hornavan. In our measured transect, we found a statistically significant linear decrease for ammonium and a small linear increase for nitrate with distance downstream from the fish farm. We didn't observe this for phosphate. When we looked at algae biomass, we compared national monitoring data with the findings of Paltsev et al (2024). Storuman had an average of 1854 µg L^{-1} and paltsev observed averages of 1292 µg L^{-1}. This means that Storuman show algae concentrations on par with Swedens most productive lakes. The results from the water chemistry show that ammonium concentrations close to the fish farm are elevated compared to the rest of the lake. Despite a non significant effect, the results together with the algae data suggest tendencies for elevated primary production in lake Storuman. The algae concentrations close to the fish farm are relieved of nutrient deficiencies due to the high concentrations of ammonium. This is seen through the incubated bottles, which showed no increase in primary production at the farm location.

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