Demand-driven fertilization (BAG) effects on stream water chemistry

A study in the Undersvik High-yield Experimental Forest

Emil Gustavsson

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Swedish University of Agricultural Sciences, SLU
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Demand-driven fertilization (BAG) effects on stream water chemistry. A study in the Undersvik High-yield Experimental Forest.

Effekter av behovsanpassad gödsling (BAG) på vattenkemi. En studie i Undersvik produktionspark.

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Abstract

Forests have a vital role in the transition to a bio-based economy and the mitigation of climate change since they are carbon sinks and provide sustainable wood products. Despite Sweden's long tradition of forest management, which has historically seen forest stock doubling at the same time as harvesting practices have become more sustainable, current trends indicate a nearing of national capacity for wood production. This challenges the forest industry, which now faces the need to enhance biomass production efficiently and innovate in silviculture to meet rising demands without compromising environmental and sustainability standards. This report aims to explore *Behovsanpassad gödsling* (BAG), or demand-driven fertilization in English, as a possible solution. BAG aim to increase growth rates while minimizing nitrogen leakage—a primary concern with conventional fertilization methods that risk eutrophication and biodiversity loss. The main focus of this thesis lies on investigating and analysing the effects that this silvicultural measure has on the stream water chemistry. This was done through utilizing data in the form of water samples from streams where BAG fertilization has been performed in the catchment area at the new operational-scale experiment at Undersvik (Project start in 2020). Water was also sampled from nearby streams without BAG influence, and from locations further downstream from the BAG treatments to see if any effects were propagated further downstream. Initial findings suggest no statistically significant impact of BAG on water chemistry in terms of nitrogen leakage, compared to reference sites. However, observed peaks and extreme values in chemical compounds indicate potential localized, short-term effects of BAG treatment. In conclusion, we can say that at this point in the Undersvik study, BAG presents a promising alternative to conventional fertilization. To judge whether BAG has potential for reduced environmental impact, longer-term studies of water chemistry and other aspects including biodiversity and forest growth are needed to fully understand the benefits and limitations.

Keywords: Demand-driven fertilization/*Behovsanpassad gödsling* (BAG), nitrogen, forests, silviculture, stream water chemistry, environment.

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Abbreviations

BAG	Demand-driven fertilization/*Behovsanpassad gödsling*
C	Carbon
DOC	Dissolved organic carbon
Dis-N	Dissolved organic nitrogen
HYEF	High-yield experimental forest
N	Nitrogen
NH_4	Ammonium
$NO_2 + NO_3$	Nitrate and Nitrite
PO_4	Phosphate
TOC	Total organic carbon
Tot-N	Total organic nitrogen

1. Introduction

1.1 Background

Forests, and the wood that they produce are recognised as a key natural resource for both the transition to a biobased economy and the mitigation of climate change (Streck and Scholz, 2006, Eyvindson et al., 2018). A forest that has been sustainably managed can play a crucial role in mitigating carbon dioxide (CO_2) emissions, such as serving as a carbon (C) sink through the absorption of C into tree biomass and the soil (Canadell and Raupach, 2008, Bonan, 2008). Furthermore, C storage increases when harvested wood products go into long-term uses like house construction, or are used to substitute fossil fuels or energy-intensive materials (e.g. concrete) (Lippke et al., 2010). The biomass derived from sustainably managed forests is typically regarded as "C neutral", as its utilization for bioenergy entails emissions that are later recaptured through forest regrowth, resulting in a net zero C footprint (Lundmark et al., 2014).

The increasing need for forest products and services, coupled with rising tensions over land use, highlights the urgency of crafting strategies to enhance the availability of resources and ecosystem services across entire landscapes (Svensson et al., 2023). During the 20th century, the production and growth of the Swedish forests has consistently outpaced the annual rate of forest harvesting, as the standing stock in Sweden has nearly doubled, and with each tree harvested, a minimum of two new trees are planted in its place. (Lundmark et al., 2014, Kumar et al., 2021). This, however, is a trend that may be changing. The average mean annual increment increased by approximately 65 % since 1950. This in turn gave way for a steady increase in both the growing stock of timber, as well as for the timber harvest. In this time, there was a notable uptick of over 70% in total harvest, paralleled with a rise of about 50% in the overall timber stock. Nevertheless, in the present day, reported fellings closely approach the national capacity, with reports indicating that fellings surpass 80% of the annual increment (Bostedt et al., 2016). Under the current circumstances, the forest industry has nearly reached the limit regarding its utilization of the Swedish forest resource, with imports increasing over time. In 2019, the Swedish forest industry consumed roughly 80 million m^3 of roundwood, exceeding the harvested volume of approximately 70 million m^3, with the pulp industry standing as the main importer of roundwood, importing 7 million m^3 in order to maintain production. Forecasts also suggest an additional 5 million m^3 rise in consumption by 2035 (Nordström et al., 2021). Thus it has become obvious that further increasing the utilization of forest products and ecosystem services relies on enhancing biomass production efficiency and advocating for innovative methods to optimize the utilization of wood and other resources derived from forests (Regeringskansliet, 2018). This is where silvicultural methods such as clonal forestry, reforestation with exotic species, and fertilization comes in as viable options for this purpose, since these alternatives have the potential to almost double the total annual growth in Sweden (Larsson et al., 2008, Nilsson et al., 2011).

Sweden is well known for its forest and forestry. However, it is also known that the boreal forests dominating the Swedish landscape are not especially fast growing. This is due to several factors including climate (characterized by short summers and long winters), slow weathering bedrock, and limited nutrient availability. Plant growth, and subsequently wood production, is usually limited by a low supply of nitrogen (N) (Tahovská et al., 2020, Bonan and Shugart, 1989, Matthews and Nesje, 2022). This has been shown through long-term nutrient optimization experiments where, the nutrient availability, and primarily N, is the biggest limiting factor regarding forest productivity in boreal and northern temperate forests (Kalliokoski et al., 2013). There are no documented instances of N release from the forested Fennoscandian bedrock shield, predominantly composed of granites and gneisses. Consequently, atmospheric N deposition and biological N fixation stand out as the principal recognized external sources of N for soil organisms and plants in the region. The total N deposition in Fennoscandian boreal forests varies across Sweden, spanning from 10–15 kg N ha^{-1} $year^{-1}$ in the south to 1–3 kg N ha^{-1} $year^{-1}$ in the north (Högberg et al., 2017, Sponseller et al., 2016). A study conducted by Gundale et al. (2011) concluded that about 70% of the global boreal forests has deposition rates at or below 3 kg ha^{-1} $year^{-1}$. This explains the deficiency of N in forests of the boreal region. The low availability of N, is also due to a major part of N being bound in soil organic matter which is not accessible for the trees (Laudon et al., 2011b).

However, this limiting factor is something that can, to some degree, be altered by forest fertilization with N. The idea of fertilizing forests, adding N for a better growth increment, comes from the mid-19th century and the German chemist Justus vin Liebig, but it was not until the 1960s that fertilization was used as a silvicultural measure (Hedwall et al., 2013). N fertilization stands out as one of the most economically efficient silvicultural techniques for boosting yield in boreal forests. The profitability of timber harvesting can see a nearly 15% rise when forest stands receive fertilization a decade prior to final felling (From et al., 2015, Nilsen, 2001). Approximately 10% of the productive forest land in Sweden has been fertilized on at least one occasion in the last century (From et al., 2015). The usual way of performing a fertilization in the Swedish rotation system is adding between one to three doses of N in the second half of the rotation period. This can increase the production by 13-20 m^3 per ha. The usual amount to apply is 150 kg N per ha (Skogsstyrelsen, 2023). Previous research has indicated that implementing fertilization in this manner only influences the specific stand for up to 10 years following the last application of N. Furthermore, a more recent investigation, focusing specifically on the residual effects of fertilization across forest stand rotations, revealed that the growth of five-year-old pine seedlings remained unaffected by site fertilization conducted three to nine years prior to the harvest of the previous stand rotation. This in turn, lends credence to the notion that the long-term effects of N application are either non-existent or extremely limited (From et al., 2015, Johansson et al., 2013). Most of the forest fertilization studies conducted in northern Europe have been done on older or middle-aged forests. There are reasons to believe that N limitation is present in younger forests as well, as there tends to be a high demand for nutrients during the initial stages of stand growth. This high demand could potentially restrict the expansion of leaf area and delay the closure of the canopy (Bergh et al., 2005, Brockley, 2010).

But even though N fertilization is a silvicultural measure with a well-documented positive effect on the growth increment of trees, even if short-term, this does not say anything about potential drawbacks. For instance, although a proportion of the N added by fertilization is taken up by the trees, up to two thirds of the N remains in the soil. Therefore one of the biggest concerns regarding the environmental impacts of N fertilization is the risk of nutrient leakage (Hedwall et al., 2013), even though the levels of inorganic N released from forest soils to streams can be quickly reduced by in-stream processes (Futter et al., 2011). Increased nutrient levels in surface waters, commonly termed eutrophication, foster heightened floral and faunal biomass, including increased risk for algal blooms, growth of rooted vegetation, and declines in biodiversity (Ansari et al., 2010). The potential impacts of increased nitrate losses to streams after forest fertilization on downstream aquatic ecosystems are of particular concern for the Baltic Sea. Here, the accumulation of organic matter in sediments has drastically depleted oxygen levels, resulting in widespread hypoxia (Murray et al., 2019). Thus increased N loading from the forest landscape could result in undesirable alterations of the structure and function of aquatic ecosystems in streams, lakes, and seas alike (Smith et al., 1999).

Furthermore, even within the forest soil, there can be risks for soil acidification through nitrification and soil exchange acidity, as well as toxic effects on microorganisms (Lundin and Nilsson, 2021, Pukkala, 2017). The concern for biodiversity is present not only for aquatic ecosystems, but for terrestrial ecosystems as well. Strengbom and Nordin (2008), in their study on the effects of forest fertilization on ground vegetation, described how the residual effects of fertilization were substantial, with a large change in the abundance of common species, which decreased overall biodiversity. Additionally, it was noted that employing fertilization as a standard practice in silviculture could lead to fertilized forests ultimately exhibiting a completely different vegetation composition, compared with unfertilized forests. The conventional method of fertilization thus makes it hard to keep track of where the N ends up and leads to negative effects affecting aquatic as well as terrestrial environments. Another thing to consider with forest fertilization is that during the initial years after the silvicultural measure have been practised, the greatest diameter growth occurs in the upper parts of the stem, making the trees more susceptible to wind and consequently windfelling (Saarsalmi and Mälkönen, 2001). A study conducted by Laiho (1987), showed that the occurrence of fallen trees was twice as high during the first years after fertilization, and that the susceptibility continued to increase until year 4, after which it began to decrease.

This conundrum, where fertilization has the potential to increase the growth of Sweden's boreal forests, but also inflict negative environmental impacts, creates an opportunity for research to develop new and better ways of performing forest fertilization. One possible method to research in this regard is *behovsanpassad gödsling* (BAG), or demand-driven fertilization in English. The method is built on applying fertilizer on multiple occasions to keep the forest stand´s growth increment as high as possible, whilst simultaneously mitigating nutritional leakage by utilizing the high demand for N in the initial stages of the stand rotation. The research that has been conducted on BAG includes, an experiment at Flakaliden (60 km west of Umeå), and Asa (37 km north of Växsjö). Both of these were led by Prof. Sune Linder (Bergh et al., 1999). Even earlier fertilization studies were conducted in Stråsån, Norrliden and Lisselbo under the leadership of Prof. Carl Olof Tamm (Högberg and Linder, 2014) as well as at Jädraås (Persson, 1980). The studies on optimizing tree fertilization over the course of three decades have shown that it is norther the growth rates of particular tree species, nor the harsh climate that are the limiting factors for growth in Swedish forests, but the nutrient availability, predominantly N (SLU, 2021, Ryan, 2013). However, there is a need for operational trials to further deepen the insights on the new BAG fertilization strategy (Skogforsk, n.d.-a). One of these studies is the Asa High-yield Experimental Forest (HYEF) which has been ongoing since 2009, with an area of

1700 ha, of which 1485 ha is productive forest. Several different silvicultural measures are being used to increase forest production, including BAG. In Asa BAG have been conducted in spruce stands since 2010, where the N fertilization is applied in the spring every second year (SLU, 2022).

This thesis, reports on a new, operational scale experimental forest at Undersvik, located near Simeå, between Bollnäs and Ljusdal, initiated by Sveaskog in 2020. In this newly opened Undersvik HYEF with an area of 1600 ha, BAG fertilization is being tested on a landscape level to study how this new method of fertilization affects forest production, as well as N leaching into nearby streams (Skogforsk, n.d.-b).

1.2 Aim of the study and hypothesis

In this report, the purpose is to investigate and analyse the effects of BAG on stream water chemistry through statistical testing of the data collected so far by the Undersvik HYEF, supported by literature review. Thus, I intend to investigate the potential impact of BAG on water quality, specifically focusing on N leakage, using the BACI (before-after control-impact) designed experiment that has been conducted at Undersvik. My focus will also be on comparing the BAG method with conventional fertilization, and exploring whether this type of fertilization could be a viable option in the future in Swedish forests. This will be done by answering three research questions:

1. Has the BAG treatment had a noticeable effect on the stream water chemistry at the Undersvik HYEF?;
2. Has BAG treatment had less of an effect compared to conventional fertilization?;
3. Can BAG be seen as a plausible substitute to conventional fertilization in Swedish forestry?

I hypothesize that based on the previous literature, an observable effect on the stream water chemistry should be expected, though not as severe as compared to conventional fertilization practices, since the demand for N is likely to be high in the initial stages of the stand formation.

To answer these research questions, this study makes use of the stream monitoring that Sveaskog established in August 2020, nine months before the first BAG fertilization began. Three headwater streams (catchment areas 30-130 ha) were chosen as controls, another three headwaters in a similar size range have had

BAG implemented on their catchments. An additional three stations were measured further downstream from these headwaters to see how far downstream eventual BAG effects could be observed. This report is based on data from the pre-treatment period, and the first two years after BAG applications were started in May 2021.

2. Method and material

2.1 The Undersvik project

The Undersvik project is a High-yield Experimental Forest (HYEF), in which fertilization is being tested at the operational scale in forestry while gathering empirical data. More specifically the effects of BAG fertilization on the growth of trees, as well as its effects on the stream water chemistry are being studied. Fertilization in Undersvik was planned for year 1, 2, 4, 7 and 10, then every 10^{th} year until clearcut. The amount of fertilization to be added is 100 kg N ha^{-1} in the 1^{st} year, then 150 kg N ha^{-1} for the rest of the treatments. The total area of the HYEF is 1600 ha, and fertilizations up until 2023 are reported in Table 1. The fertilized area increased from the 1^{st} to the 2^{nd} fertilization, as new juvenile forest was added for fertilization. The fertilization was practised via helicopter, and the fertilizer used was ammonium nitrate (NH_4NO_3). This was applied to sites 4, 5, and 6. The black checkered area in Figure 1 represents the reference area that is not fertilized, and the yellow checkered zones the fertilized areas.

Table 1. Summary table on the fertilizations practised at Undersvik.

Fertilization	*Date*	*Area*
1st	27-28 May 2021	154 ha
2nd	21-22 June 2022	190 ha

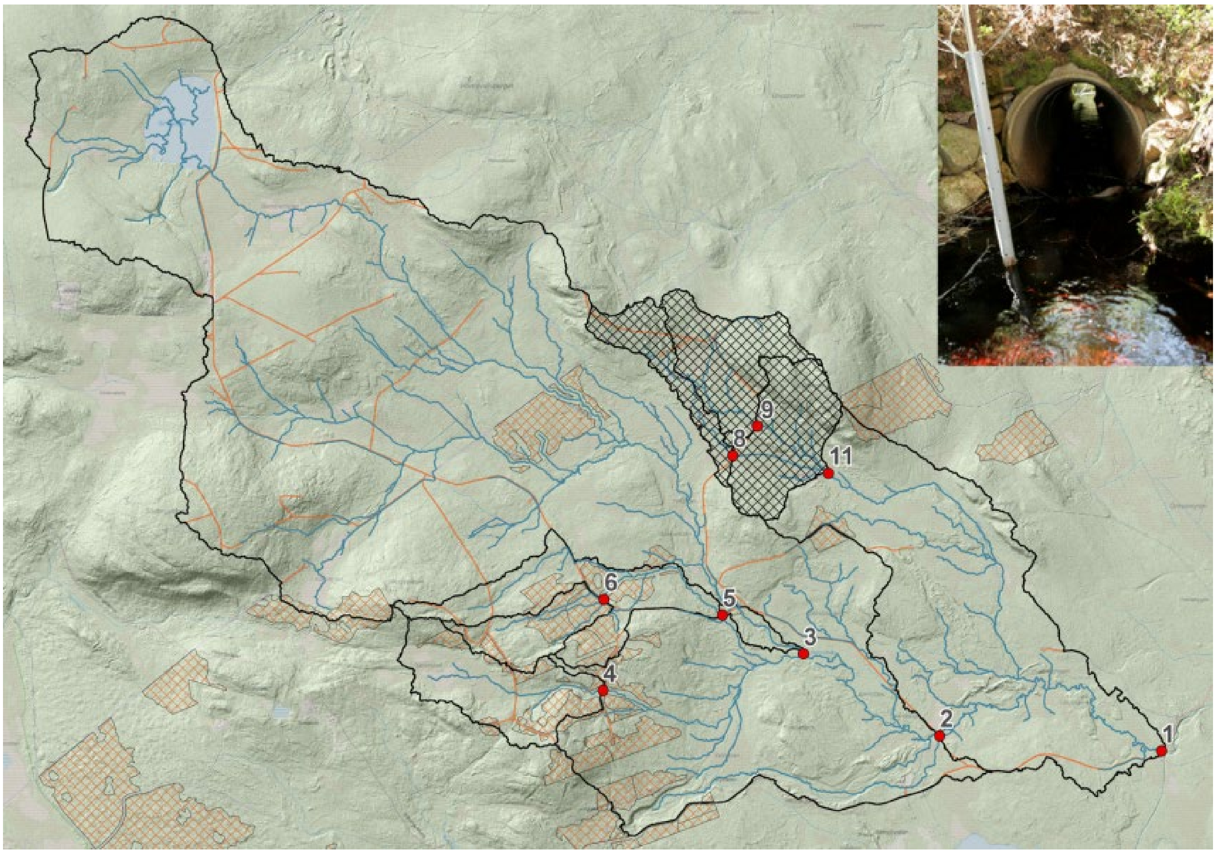

Figure 1. Map of the Undersvik HYEF catchments and sampling sites. Downstream including sites 1, 2 and 3, BAG treatment sites 4, 5, and 6, Reference/control sites 8, 9 and 11.

Table 2. List of the different site catchment sizes. Parenthesis includes names for specifying the type of site. D represent downstream site, C control/reference site, and Bag fertilized site.

Site	Catchment area [km^2]
1 (1D)	19.6
2 (2D)	15.3
3 (3D)	11.4
4 (1Bag)	0.6
5 (2Bag)	1.0
6 (3Bag)	0.3
8 (1C)	0.3
9 (2C)	0.5
11 (3C)	1.3

2.2 Data analysis

The data received came in the form of lab analysis results from labs in Umeå and Uppsala. To clarify, I received the results from the lab analysis, but did not partition in it. The compounds analysed in the water samples from Undersvik were dissolved organic carbon (DOC), dissolved organic nitrogen (dis-N), ammonium (NH_4-N), nitrate and nitrite (NO_2 + NO_3-N), as well as phosphate (PO_4-P) and other elements. As the analysis was initially performed at the SLU Umeå lab these were the first chemical compounds measured. Later, the analysis switched to the SLU Uppsala lab, total organic carbon (TOC) was used instead of DOC, and total organic nitrogen (tot-N) instead of dis-N. Analyses were made simultaneously on three occasions in the spring of 2021 during the shift from one lab to the other. These were analysed to see if there were any systematic differences. There were in fact measurable differences. As these small differences affected samples from the control and treatment sites in the same way, these were not deemed to affect the overall issue of seeing changes created by fertilization. Therefore, for the three months with water chemistry analysed in both Umeå and Uppsala, the average of the values was used.

Processing and utilization of the data were performed in the program Excel, where the observed concentrations were reported as mg l^{-1}. To get daily time series from the monthly sampling, linear interpolation was used in between the observed monthly values. These were later used to create average monthly values, also in Excel. After that, exports from the catchment sites were calculated, utilizing the Swedish Metrological and Hydrological Institute (SMHI) and their flow data from Undersvik in combination with the given areal data of each catchment size. Thus, calculating the total amount of the different chemical compounds exported from the catchment sites when water flow and catchment size is considered. The daily waterflow was calculated in l/s, based on the modelled data from Site 1C (SMHI designation: 14593; SWEREF 99 coordinates: 564425, 6825629). This was used to get the waterflow for all sites, and then used together with the interpolated values of each site and chemical compound to get the exports s^{-1}. These were then utilized to calculate daily averages, and finally monthly averages.

2.3 Statistical testing

In cooperation with and under the supervision from the statistician at the Forest Faculty in SLU Umeå, and my supervisor, the choice was made to conduct three t-tests with a significance level of 0.05. One for each period before, between and after fertilizations. It was also decided to only test between the BAG fertilized and reference sites. These were deemed most likely to show any significant treatment effect. The downstream sites were thus not included. Therefore, utilizing t-tests to see if there are any statistically significant differences between the chemical compounds in the analysed water samples between the reference and BAG sites in the three different periods. The statistical testing was conducted in the programme

R (version 4.2.2) (R Core Team, 2022), where the data was reconfigured into a new Excel document, in a way that would be manageable for R to process. The three time intervals were defined, and the statistical test was conducted for both the calculated exports, as well as the concentrations.

2.4 Time series

Time series were created in Excel, plotting the observed monthly exports and concentrations over the time that the testing of the catchment sites was executed. This was done for each chemical compound separately, including all sites in each time series. Time series of the waterflow at Undersvik was also created, using the daily water flow data provided by SMHI from their web "Vattenwebb" and their search function "Modelldata per område" (SMHI, 2023b). The daily water flow data were created by SMHI using the S-HYPE Model. The HYPE (Hydrological Predictions for the Environment) model itself is a semi-distributed catchment model that simulates waterflow and substances carried by that water on its way from precipitation through different catchment compartments, with the fluxes out of the soils then routed through the channel network (including lakes) to the sea (SMHI, 2023a). The specific discharge at this station was assumed to be the discharge for all the sites sampled for water chemistry at Undersvik. Hourly water level observations are available for most of these sites, together with flow estimates by bucket and/or salt addition assessments on a few occasions, but they have not been used in this work since more processing of these data are needed to be able to produce rating curves that are needed to transform water level data to flow rates.

2.4.1 Peaks and extreme values

In the time series of water chemistry peaks that might be considered extreme values, were observed. Selection criteria were created to make for a trustworthy process in distinguishing extreme values that could be looked at more carefully. These extreme values were defined both qualitatively and objectively:

I. Subjectively defining peaks in the time series that differed markedly from the rest of the data points in the series.
II. Data points having a value at least 5 times higher than the median value. These median values expressed as kg/ha in Table 3 below.

Table 3. Limiting values to distinguish "true" extreme values for each chemical compound.

DOC/TOC	26.6
Tot-N	0.68
NH_4-N	0.02
NO_2-N + NO_3-N	0.02
PO_4-P	0.06

The peaks and extreme values that passed these criteria were then displayed in a table, separate for each chemical compound. Here the description of each data point was laid out as well, where site, date, value, if there was a fertilization in the previous 4 weeks, waterflow and whether the data point coincided with the TOC/DOC peaks were addressed. One descriptor of the peaks and extreme values that needed definition and clear classification was the waterflow class, which is shown in the Table 4 below.

Table 4. Limiting values indicating the water flow class of peaks/extreme values. Period of very low flow being the lower 10:th percentile of the water flow data, period of low flow the lower 20:th percentile, period of high flow the upper 20:th percentile of water flow. With period of normal flow being between the limiting values of low flow and high flow.

Water flow class	*Specific Discharge (mm/d)*
Period of very low flow	<0.28
Period of low flow	0.28-0.40
Period of normal flow	0.40-1.38
Period of high flow	1.38-2.21
Period of very high flow	>2.21

2.5 Comparison between TOC/DOC, dis-N/tot-N

Due to the shift in labs from Umeå to Uppsala during the analysis of the water samples, some of the chemical compounds analysed also changed. In Umeå the analysis included measuring DOC, after filtration on 0.45 µm filters, whereas Uppsala measures TOC without filtration. However, this is not deemed a problem since these compounds are comparable. Laudon et al. (2011a) they analysed the DOC concentration from 10 ml of peat pore or stream water, which was filtered through 0.45 µm filters in field and stored in high-density polyethylene bottles. The analyses showed no statistically significant differences between the filtered and unfiltered samples, indicating that DOC is a reasonable proxy for TOC. The same thing happened regarding dis-N and the tot-N. We have three samplings done in parallel, which quantify the small difference between them.

3. Results

3.1 Statistics

3.1.1 Concentrations

The results for the t-tests in Table 5 between the BAG and the reference sites did not indicate a significant difference in the concentrations of chemical compounds for any of the time periods. The first t-test accounted for the period including the start of the measurement period (August 2020) until the first fertilization (May 2021), the second include the first fertilization until the second fertilization (June 2022), and the third include the second fertilization until the end of the measurement period (August 2023).

Table 5. Resulting p-values after performing t-test on each chemical compound for difference between reference and BAG sites regarding period 0 (i.e., period before fertilization), period 1 (i.e., period between 1st and 2nd fertilization), and period 2 (i.e., period after 2nd fertilization).

Chemical compound	P-value
Period 0	
TOC	0.36
Tot-N	0.34
NH_4	0.46
$NO_2 + NO_3$	0.65
PO_4	0.82
Period 1	
TOC	0.34
Tot-N	0.34
NH_4	0.39
$NO_2 + NO_3$	0.40
PO_4	0.55
Period 2	
TOC	0.30
Tot-N	0.84
NH_4	0.24

$NO_2 + NO_3$	0.3288
PO_4	0.6987

3.1.2 Exports

In the same manner as with the statistical testing for the concentrations, we can see that the results for the exports in Table 6 did not show any statistical evidence for there being a significant difference in the exports of chemical compounds between the BAG and reference sites for any of the time periods.

Table 6. Resulting p-values after performing t-tests for difference between reference and BAG sites regarding export of chemical compounds during period 0 (i.e., period before fertilization), period 1 (i.e., period between 1st and 2nd fertilization), and period 2 (i.e., period after 2nd fertilization).

Chemical compound	**P-value**
Period 0	
TOC	0.34
Tot-N	0.29
NH_4	0.49
$NO_2 + NO_3$	0.82
PO_4	0.96
Period 1	
TOC	0.32
Tot-N	0.33
NH_4	0.42
$NO_2 + NO_3$	0.39
PO_4	0.61
Period 2	
TOC	0.29
Tot-N	0.55
NH_4	0.18
$NO_2 + NO_3$	0.33
PO_4	0.60

3.2 Time series of exports and concentrations

Below are the time series of each chemical compound. These depict the concentrations and calculated exports from each sampled site during the study, together with the water flow and are intended to provide an initial overview of how these relate. Dotted lines in the figures represent when the fertilizations were conducted. These are the time series in which extreme value data points were observed and picked.

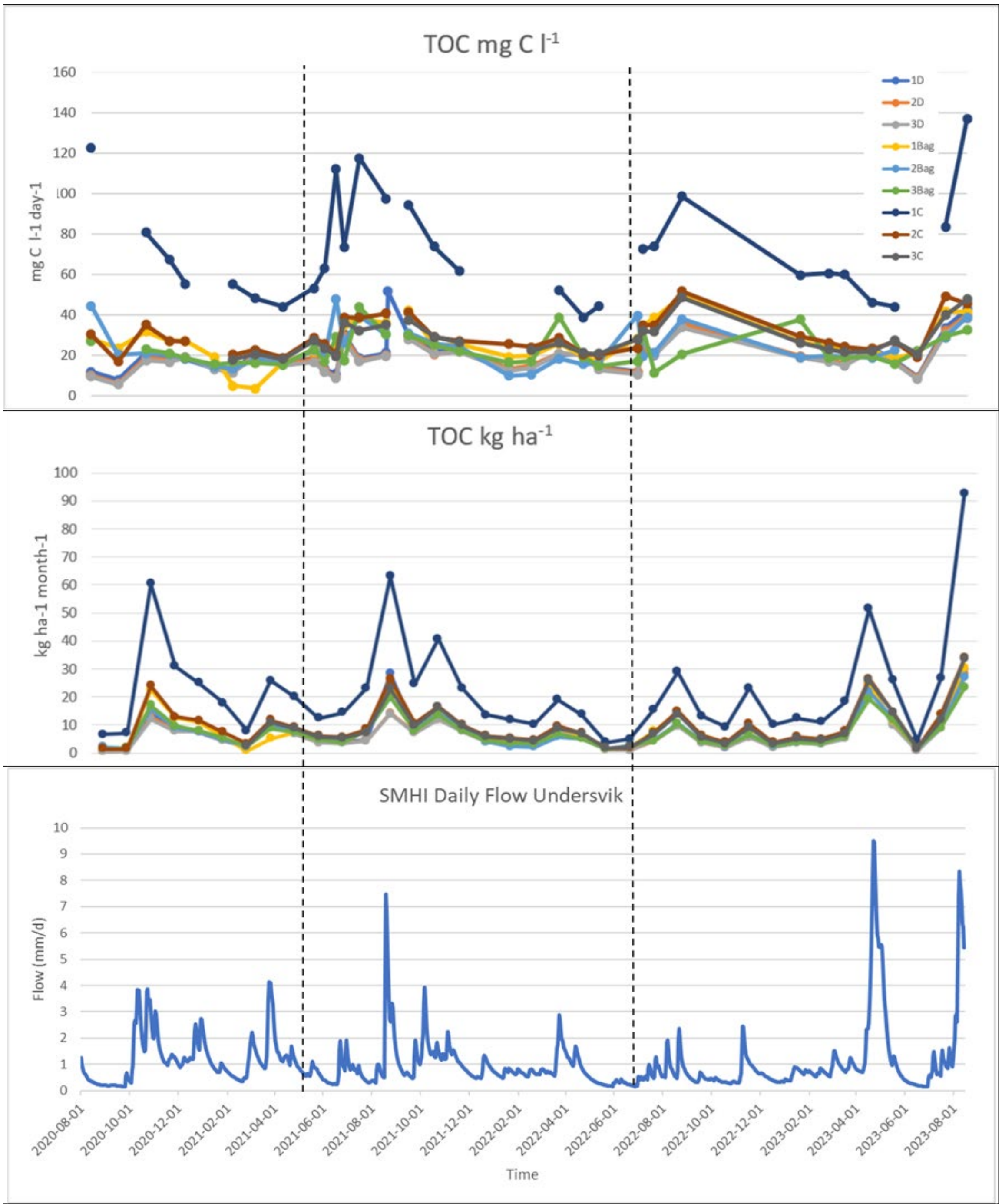

Figure 2. Time series of TOC at each site in mg C/l (upper panel). Time series of interpolated TOC exports in kg/ha (middle panel). Time series of water flow at Undersvik in mm/day (lower panel). Dotted lines represent when the fertilizations occurred.

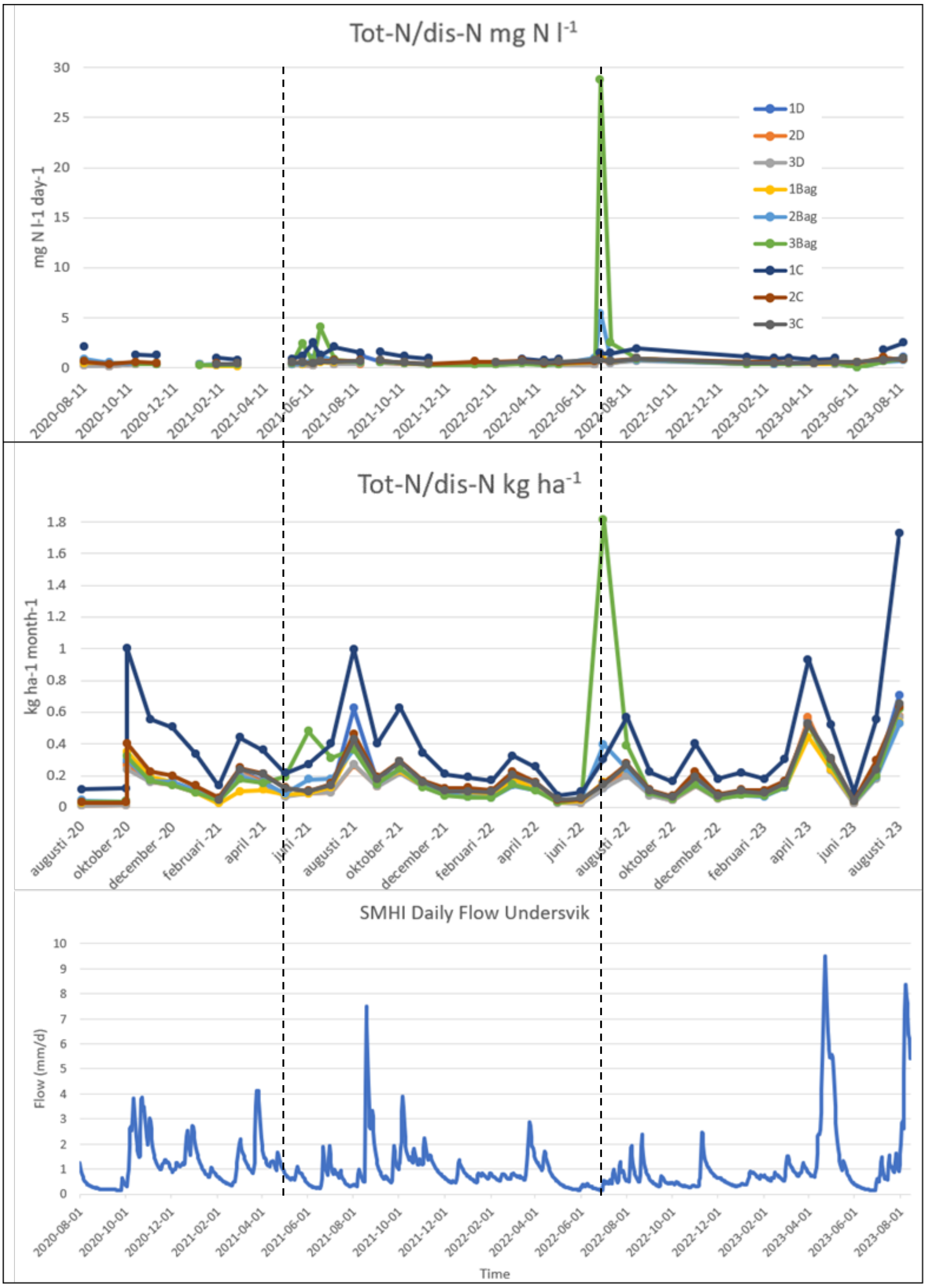

Figure 3. Time series of Tot-N samples at each site in mg N/l (upper panel). Time series of interpolated Tot-N exports in kg/ha (middle panel). Time series of water flow at Undersvik in mm/day (lower panel). Dotted lines represent when fertilizations occurred.

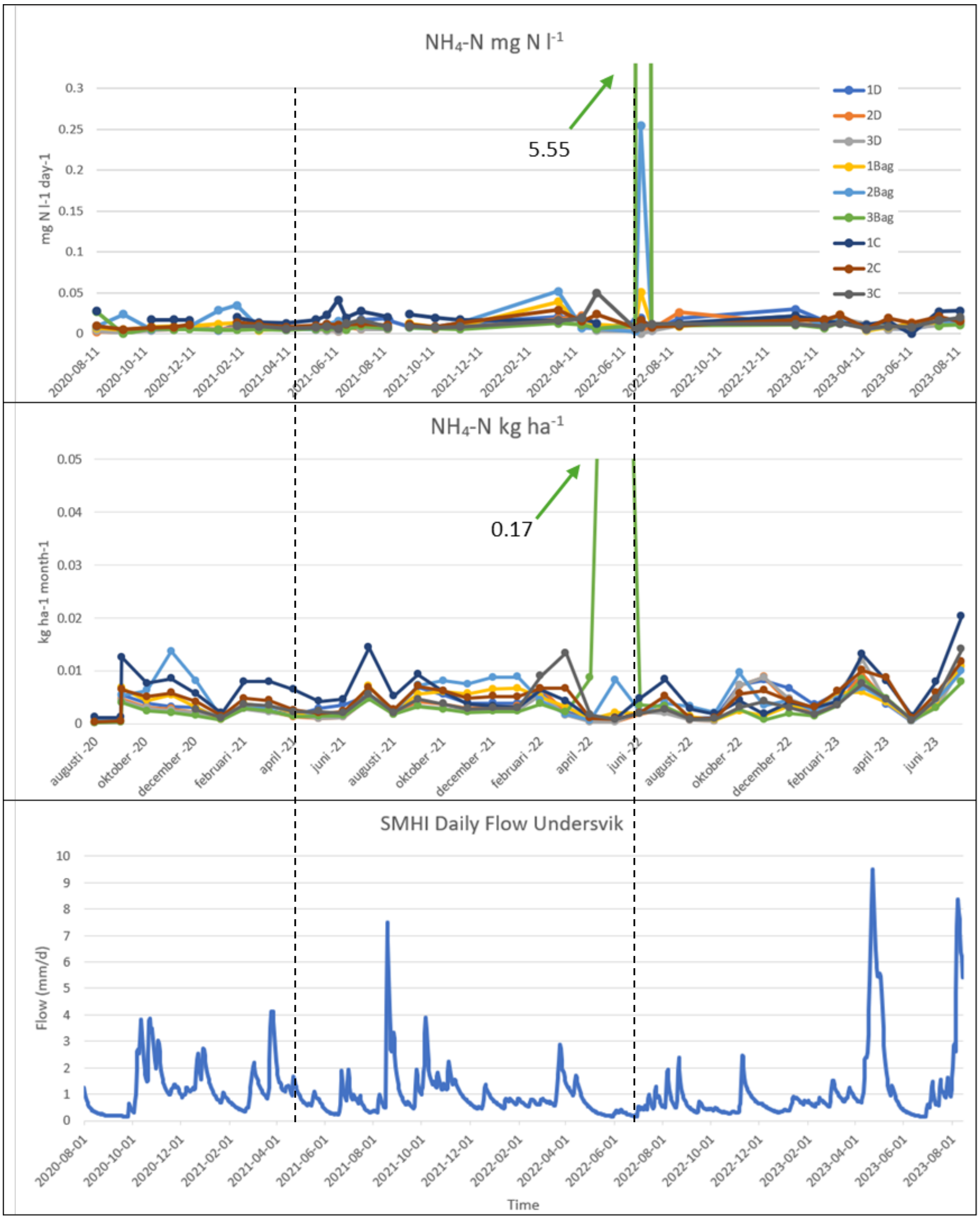

Figure 4. Time series of NH_4-N samples at each site in mg N/l (upper panel). Time series of interpolated NH_4-N exports in kg/ha (middle panel). Time series of water flow at Undersvik in mm/day (lower panel). Dotted lines represent when the fertilizations occurred.

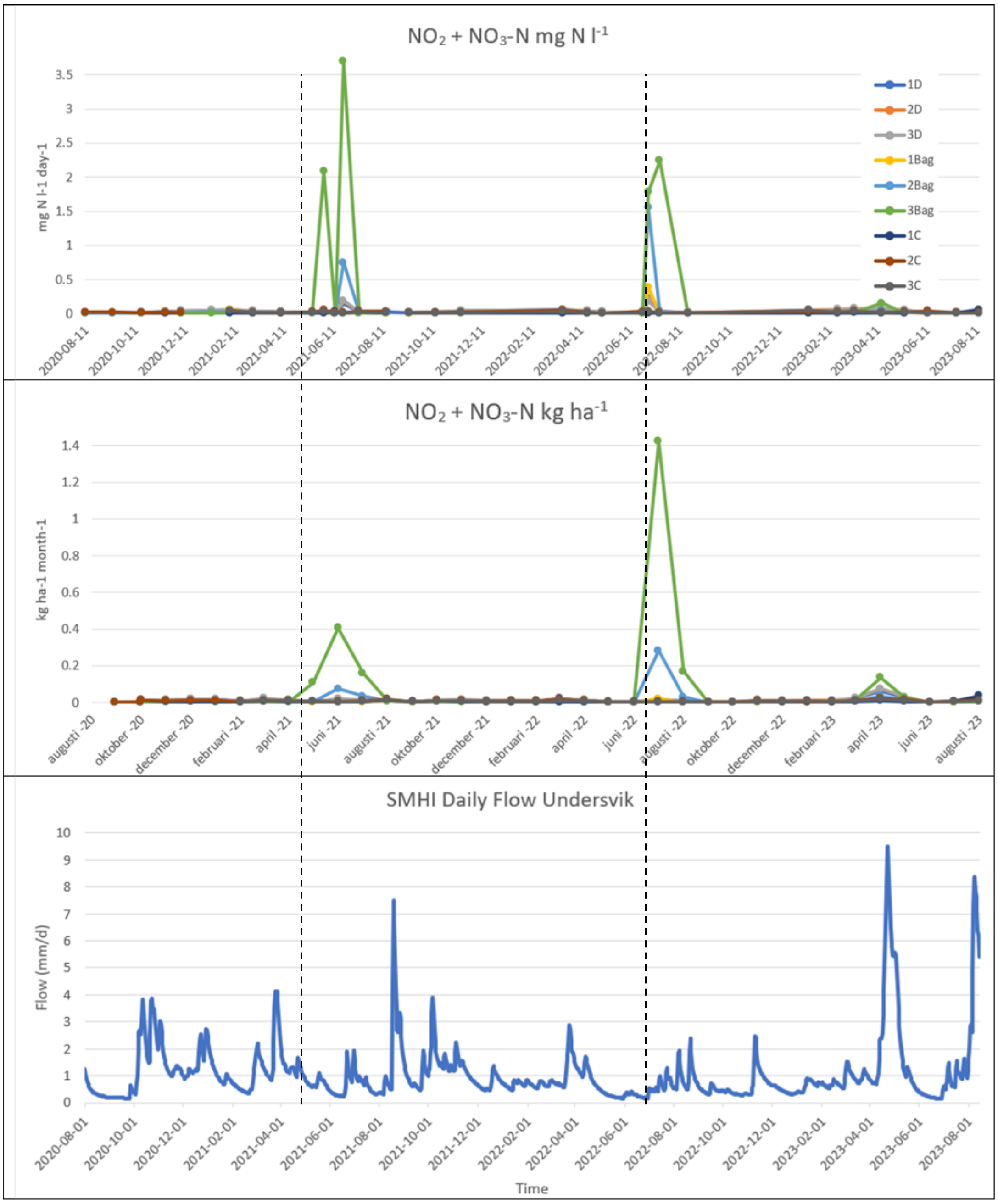

Figure 5. Time series of NO_2-N + NO_3-N samples at each site in mg N/l (upper panel). Time series of interpolated NO_2-N + NO_3-N exports in kg/ha (middle panel). Time series of water flow at Undersvik in mm/day (lower panel). Dotted lines represent when the fertilizations occurred.

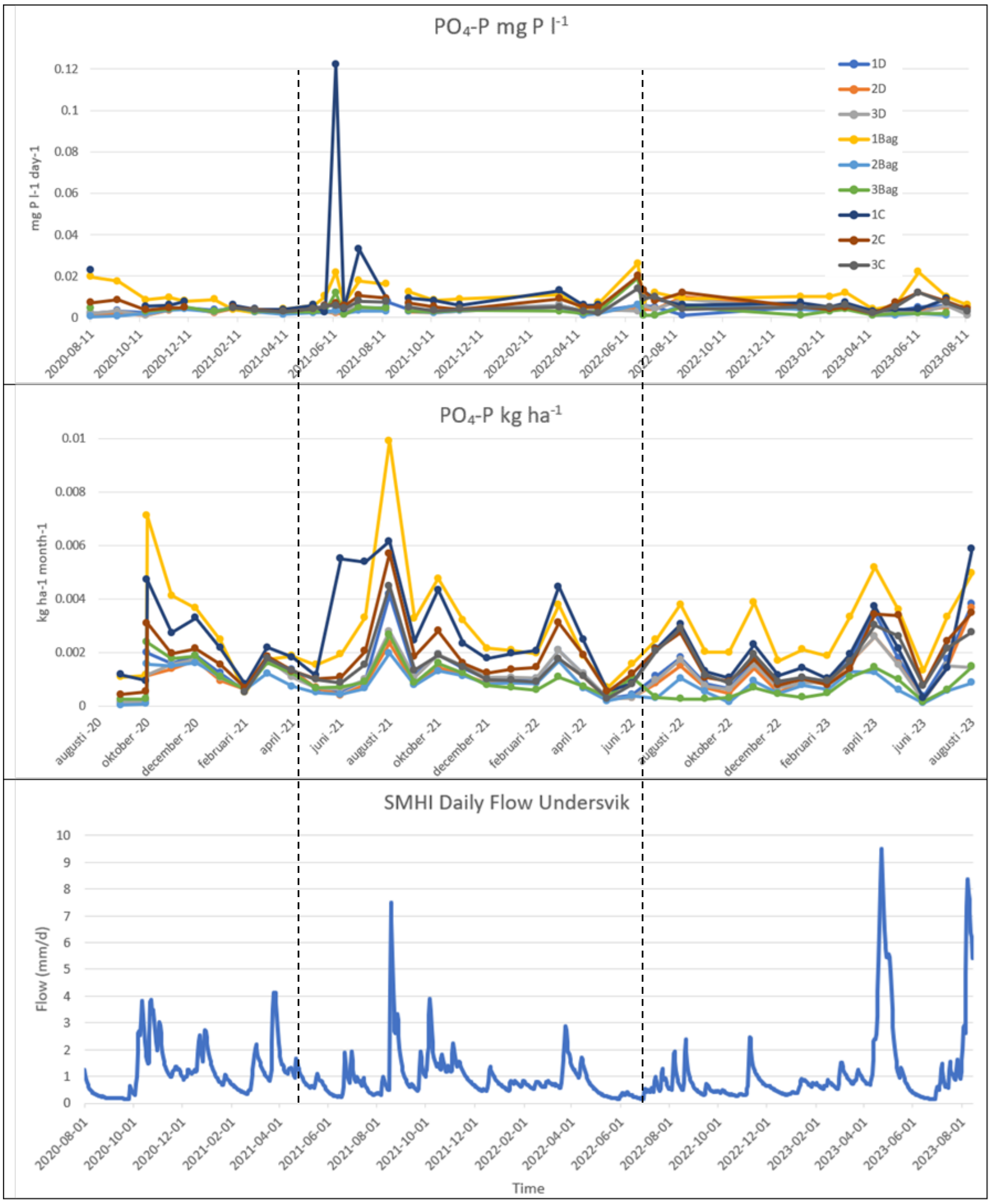

Figure 6. Time series of PO_4-P samples at each site in mg P/l (upper panel). Time series of interpolated PO_4-P exports in kg/ha (middle panel). Time series of water flow at Undersvik in mm/day (lower panel). Dotted lines represent when the fertilizations occurred.

3.3 Exports peaks and extreme values

Below in Table 7, 8, 9 and 10 are the observed peaks and extreme values from the time series for each separate chemical compound, using the criteria for the peaks and extreme values explained in the methods and material section.

Table 7. Peaks/extreme values of DOC/TOC exports defined as observed data points in the time series that differ markedly from the rest of the data points in the series, with the quantitative criteria being a value five times higher than the median concentration for each chemical compound. Having the value 26.6 kg/ha for DOC/TOC. Orange cells indicate fertilized sites, blue reference sites, and grey downstream sites.

Plot	Site	Date	Value	Fertilization previous 4 weeks	Flow	Coincides with TOC/DOC peak
DOC/TOC	1C	2020-10	60.5	No	Very high	-
DOC/TOC	1C	2021-08	63.0	No	High	-
DOC/TOC	1C	2023-04	51.5	No	Very high	-
DOC/TOC	1C	2023-08	92.6	No	Very high	-

Table 8. Peaks/extreme values of Tot-N exports defined as observed data points in the time series that differ markedly from the rest of the data points in the series, with the quantitative criteria of being a value five times higher than the median concentration for each chemical compound. Having the value 0.68 kg/ha for Tot-N. Orange cells indicate fertilized sites, blue reference sites, and grey downstream sites.

Plot	Site	Date	Value	Fertilization previous 4 weeks	Flow	Coincides with TOC/DOC peak
Tot-N/dis-N	3Bag	2022-07	1.81	Yes	Normal	No
Tot-N/dis-N	1C	2020-10	1.00	No	Very high	Yes
Tot-N/dis-N	1C	2021-08	1.00	No	High	Yes
Tot-N/dis-N	1C	2023-04	0.93	No	Very high	Yes
Tot-N/dis-N	1C	2023-08	1.73	No	Very high	Yes

Table 9. Peaks/extreme values of NH_4 exports defined as observed data points in the time series that differ markedly from the rest of the data points in the series, with the quantitative criteria of being a value five times higher than the median concentration for each chemical compound. Having the value 0.02 kg/ha for NH_4-N. Orange cells indicate fertilized sites, blue reference sites, and grey downstream sites.

Plot	Site	Date	Value	Fertilization previous 4 weeks	Flow	Coincides with TOC/DOC peak
NH_4-N	3Bag	2022-06	0.17	Yes	Very low	No
NH_4-N	1C	2023-08	0.02	No	Very high	Yes

Table 10. Peaks/extreme values of NO_2 and NO_3 exports defined as observed data points in the time series that differ markedly from the rest of the data points in the series, with the quantitative criteria of being a value five times higher than the median concentration for each chemical compound. Having the value 0.02 kg/ha for NO_2-N + NO_3-N. Orange cells indicate fertilized sites, blue reference sites, and grey downstream sites.

Plot	Site	Date	Value	Fertilization previous 4 weeks	Flow	Coincides with TOC/DOC peak
NO_2-N + NO_3-N	*1D*	*2023-04*	*0.06*	*No*	*Very high*	*Yes*
NO_2-N + NO_3-N	*2D*	*2023-04*	*0.07*	*No*	*Very high*	*Yes*
NO_2-N + NO_3-N	*3D*	*2023-04*	*0.07*	*No*	*Very high*	*Yes*
NO_2-N + NO_3-N	*2Bag*	*2021-06*	*0.07*	*Yes*	*Normal*	*No*
NO_2-N + NO_3-N	*2Bag*	*2021-07*	*0.03*	*No*	*Normal*	*No*
NO_2-N + NO_3-N	*2Bag*	*2022-07*	*0.28*	*Yes*	*Normal*	*No*
NO_2-N + NO_3-N	*2Bag*	*2022-08*	*0.03*	*No*	*Normal*	*No*
NO_2-N + NO_3-N	*2Bag*	*2023-04*	*0.04*	*No*	*Very high*	*Yes*
NO_2-N + NO_3-N	*3Bag*	*2021-05*	*0.11*	*Yes*	*Normal*	*No*
NO_2-N + NO_3-N	*3Bag*	*2021-06*	*0.41*	*Yes*	*Normal*	*No*
NO_2-N + NO_3-N	*3Bag*	*2021-07*	*0.16*	*No*	*Normal*	*No*
NO_2-N + NO_3-N	*3Bag*	*2022-07*	*1.42*	*Yes*	*Normal*	*No*
NO_2-N + NO_3-N	*3Bag*	*2022-08*	*0.17*	*No*	*Normal*	*No*
NO_2-N + NO_3-N	*3Bag*	*2023-04*	*0.13*	*No*	*Very high*	*Yes*
NO_2-N + NO_3-N	*1C*	*2023-08*	*0.04*	*No*	*Very high*	*Yes*

Table 11. Peaks/extreme values of PO_4 defined as observed data points in the time series that differ markedly from the rest of the data points in the series, with the quantitative criteria of being a value five times higher than the median concentration for each chemical compound. Having the value 0.06 kg/ha for PO_4-P. Orange cells indicate fertilized sites, blue reference sites, and grey downstream sites.

Plot	Site	Date	Value	Fertilization previous 4 weeks	Flow	Coincides with TOC/DOC peak
PO_4-P	*1Bag*	*2020-10*	*0.01*	*No*	*Very high*	*Yes*
PO_4-P	*1Bag*	*2021-08*	*0.01*	*No*	*High*	*Yes*

3.3.1 Total peaks and extreme values

Above in Table 4, 5, 6, 7 and 8 we have the summarized peaks and extreme values from the export time series divided into each table by chemical compound. There were a total of 28 peaks and extreme values spread throughout the export time series, where 15 of them were observed in the BAG sites (54 %), 10 (36 %) in the reference sites, and 3 (11 %) in the downstream sites. Only 7 (47 %) of the BAG peak occurred 4 weeks after fertilization. Even though a bigger percentage of the BAG sites could be seen as “near” the fertilization.

When it comes to the water flow classes defined as in Table 4 in the material and method section, 14 (50 %) of the peaks and extreme values occurred during very high flow, 3 (11 %) during high flow, 10 (36 %) during normal flow, and 1 (4 %) during very low flow.

How the peaks of total N, NH4, NO2 + NO3 and PO4 coincided with the peaks of the DOC/TOC exports were also observed. Here 13 (46 %) of the peaks/extreme values could be seen to coincide with the DOC/TOC peaks.

3.3.2 DOC/TOC

The peaks that occurred in the DOC/TOC time series came only from the reference sites, and exclusively from Site 1C. Three (75%) of the peaks occurred during very high flow and one (25%) during high flow.

3.3.3 Tot-N

For the tot-N, four (80%) of the peaks came from the reference sites, and all of them from Site 1C, whereas one (20%) came from the BAG sites, and in this case Site

3Bag. Here three (60%) of the peaks occurred during very high flow, one (20%) during high flow, and lastly one during normal flow. All that occurred during high and very high flow came from reference sites, and the normal flow from a BAG site. All the reference site peaks coincided with the DOC/TOC peaks, while the BAG site peak did not. The BAG site peak also occurred within four weeks of a fertilization being conducted.

3.3.4 NH_4-N

Regarding the NH_4, there were only two peaks, one from BAG Site 3Bag and one from reference Site 1C. The BAG did have fertilization in the previous four weeks. The BAG site also had a very low flow class, whereas the reference site occurred during a very high flow. Lastly, the BAG site peaks did not coincide with the peaks of the DOC/TOC, while the reference site peaks for this substance did coincide with the peaks from the DOC/TOC.

3.3.5 NO_2 + NO_3-N

In the peaks of the $NO_2 + NO_3$ we can observe that this is the chemical compound with the largest number of peaks. We can also see that most of these peaks came from BAG sites, eleven of the total fifteen peaks (73 %). Out of these eleven BAG site peaks, six were observed at Site 3Bag, and five in Site 2Bag. Five of the eleven BAG site peaks (45%) had fertilization done in the previous four weeks. Nine out the eleven (82%) BAG site peaks had the flow class normal, and the remaining two (18 %) the flow class very high. Two out of these eleven BAG site peaks coincided with the peaks of the DOC/TOC.

In these peaks only a single reference site can be found, which occurred at Site 1C. This peak appeared when the water flow was classed as very high and happened to coincide with the peaks of the DOC/TOC as well.

Interestingly, it is only in the peaks of the $NO_2 + NO_3$ where peaks from the downstream sites can be found. The three peaks observed from the downstream sites were found at Sites 1D, 2D and 3D. No fertilization had been done in the previous 4 weeks to any of the 3 peaks, and they all occurred when water flow was classified as very high, as well as all coinciding with the peaks of the DOC/TOC. One more interesting thing to observe with these three downstream sites, is that they all occurred at the same moment in time, April 2023, 10 months after the last fertilization.

3.3.6 PO_4-P

With the two peaks that occurred for the PO_4, both came from BAG Site 1Bag. No fertilization occurred in the previous 4 weeks. Flow was classed as "very high" and "high" at the time of occurrence. Lastly, both coincide with peaks of DOC/TOC.

3.4 Scatterplots/Relation to total N kg ha^{-1}

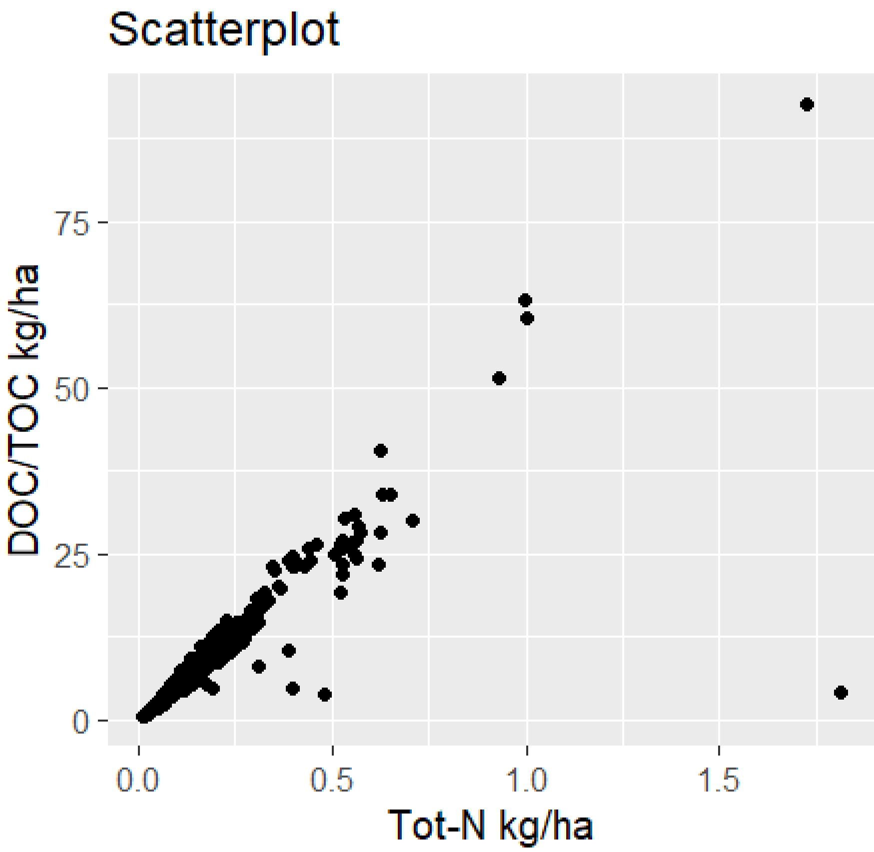

Figure 7. Scatterplot of DOC/TOC in relation to total N in kg ha^{-1}.

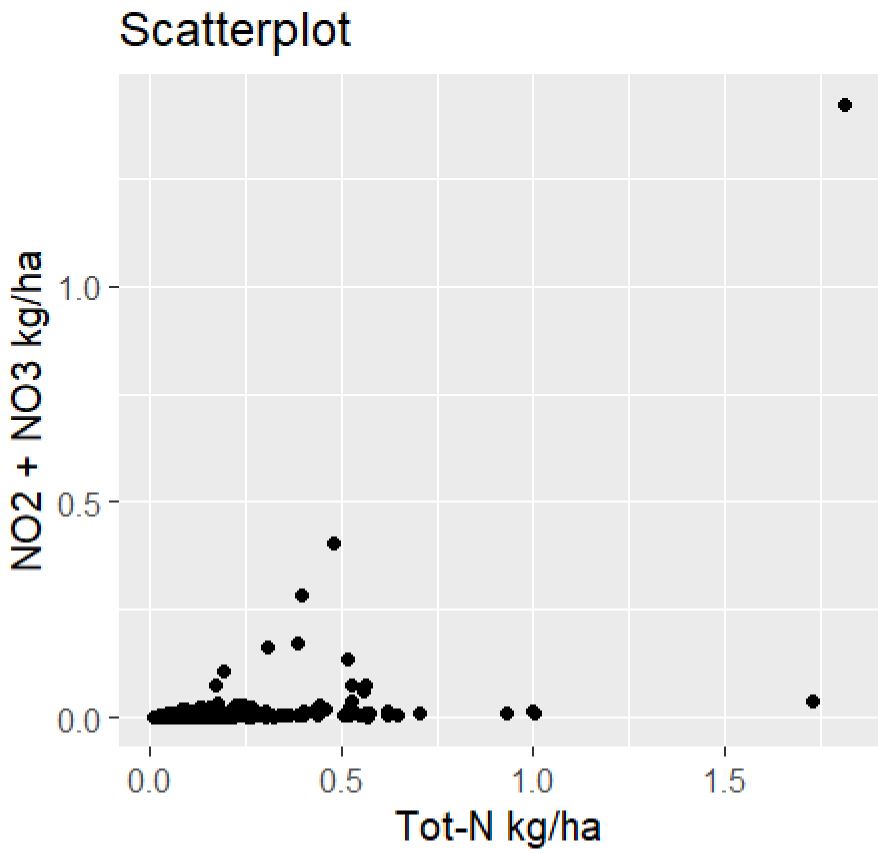

Figure 8. Scatterplot of NO_2 + NO_3 in relation to total N in kg ha^{-1}.

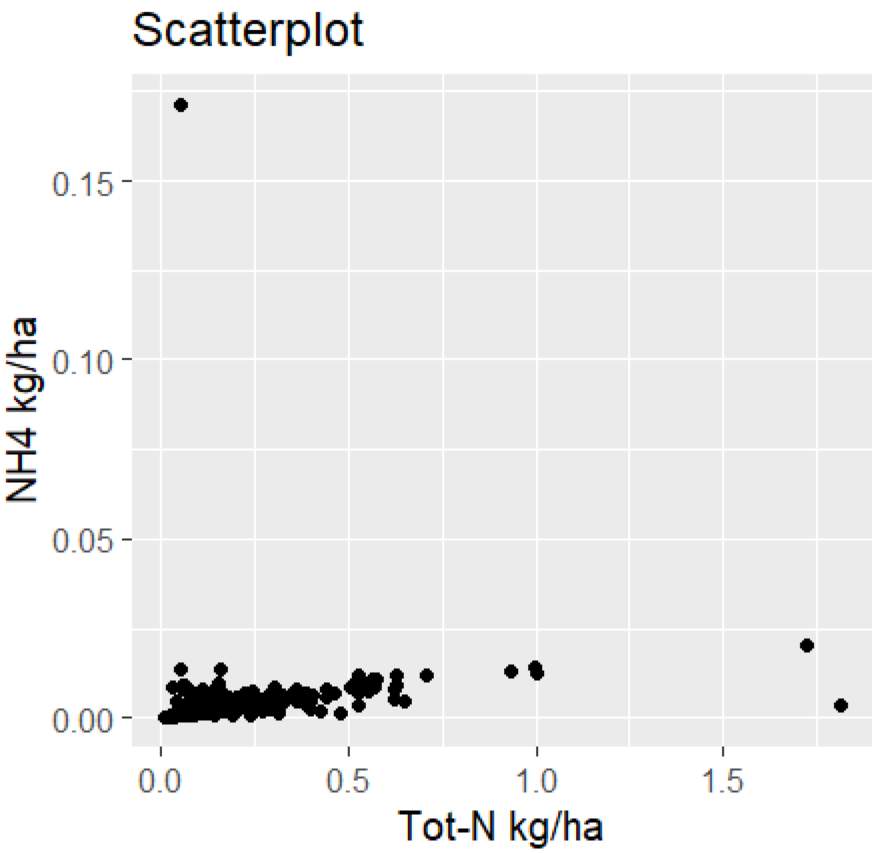

Figure 9. Scatterplot of NH_4 in relation to total N in kg ha^{-1}.

The scatterplots in figures 7, 8 and 9 above depicts the relationship between the total export N and the export DOC/TOC, NO_2 + NO_3 and NH_4. These scatterplots seem to indicate that there is somewhat of a linear relationship between the total N and DOC/TOC, and nothing of significance to indicate anything in the relationship for NO_2 + NO_3 and NH_4 to total N. Meaning a stronger correlation between the total N and DOC/TOC, whereas a weaker correlation between total N and NO_2 + NO_3, as well as NH_4.

4. Discussion

4.1 Has the BAG treatment had a noticeable effect on Undersvik?

4.1.1 Statistics

As per the statistical testing from the result section, and from what we can see in Table 2 and 3, the t-tests did not indicate any statistically significant differences between the tested reference and BAG sites, for any period or chemical compound. Why this is the case could be due to a number of reasons, but the two I would like to point out are 1) This method of fertilization does not have a large or significant effect on the stream water chemistry; and 2) The effect of the BAG fertilization treatment on the stream water chemistry is yet to be seen in this particular test, as too few fertilizations have been executed and not enough time has passed.

4.1.2 Peaks and extreme values

From just the statistical testing it might be hard to get a concrete answer to the overall question of whether BAG is impacting water quality. Thus, we will have to look at some of the other data and evidence. If we take a closer look at the peaks and extreme values that appeared in the time series for the export, we can see that across all the chemical compounds there were a total of 28 peaks and extreme values that met our qualitative and quantitative criteria. Of these, fifteen came from BAG sites, ten from reference and three from downstream. This is however not the complete picture as it does not show how specific aspects of stream chemistry behaved. When we separate the peaks and divide into chemical compounds, it looks somewhat different. For the DOC/TOC peaks, all the peaks were observed at Site 1C, which is a reference site with a large area of peatlands in the catchment. For the tot-N peaks, four out of the five peaks also came from the reference sites, Site 1C, whereas only a single DOC/TOC peak came from a BAG site. For the NH_4 peaks one came from a BAG site and one from a reference site. Then we have the inorganic N (NO_2 + NO_3) which was added in the fertilization, and which is well known for the risk of leaching from soils into streams. The inorganic nitrogen, composed primarily of nitrate, was the chemical compound with the largest number of peaks (fifteen), but also had most of its peaks (eleven) from BAG sites. The reference site $NO_2 + NO_3$ peaks came from just one headwater reference site, and the other three came from the downstream sites, all on the same sampling occasion at high flow in April 2023. Inorganic N was also the only chemical compound with observed peaks at downstream sites. Lastly for the PO_4 there were only two peaks, with both coming from a BAG site. As we can see from this, the peaks of the DOC/TOC and tot-N occurred mostly on reference sites, while the $NO_2 + NO_3$ and PO_4 were BAG site dominated. The NH_4 split between BAG and reference sites.

Peaks tended to be noted in the reference sites (for DOC/TOC and tot-N) when sampling was done during times of higher flows (above the 80^{th} percentile of flow, classified high to very high). The inorganic N peak was observed in reference sites or downstream sites were also observed at high flow. When peaks (mostly inorganic N) were observed at BAG sites, this tended to be at periods of lower flow (normal to very low). There were exceptions, but it looks like there is a general pattern where high flows can be associated with peaks of DOC/TOC and tot-N from the reference sites, or even downstream sites. But high flows were not generally associated with the inorganic N peaks observed in BAG sites. This suggests that the fertilization did lead to the inorganic N peaks at the BAG sites, even though inorganic N peaks could occur on reference sites, though less frequently.

There were ten dates where all the peaks occurred. If we look at the dates where peaks occurred at least at three sampling sites, we can see that October 2020, August 2021, July 2022, April 2023, and August 2023 were the dates where most peaks were found. Further, almost all these dates are in periods of high to very high water flow levels. July 2022 was an exception since it had a normal class flow level. The peaks that occurred on the high-flow dates also came mostly from non-BAG sites, where all dates had more observations of peaks in the reference and downstream sites, except for July 2022 where observed peaks exclusively came from BAG sites.

If we then go from reoccurring dates to reoccurring sites, there were seven sites where peaks were observed, but only three of these sites had at least three peak observations. They consisted of the BAG sites 2Bag and 3Bag, that had five and eight peak observations, as well as reference Site 1C which had ten peak observations. Of the BAG sites, Site 2Bag only showed peaks for $NO_2 + NO_3$, BAG Site 3Bag for tot-N, NH_4 and $NO_2 + NO_3$. The reference Site 1C had peaks for every chemical compound except for PO_4.

Why did these specific sites have most of the peaks? For Site 1C, a reference site, this can be connected to the fact that this site has more peatland, and thus higher DOC levels. This in turn helps explain why the DOC/TOC peaks came exclusively from Site 1C, and why most of the tot-N peaks came from this site. Peatlands are rich in both C and N, storing a third of the global soil C and upwards of 15 percent of the global soil N (Vesala et al., 2021). The DOC/TOC peaks are much easier to derive from the peatland as an explanation, whereas the tot-N is a bit foggier. But even though it is nearly impossible describe the dynamics (inputs, outputs etc.) of a peatland without having a more detailed description on the type of peatland and so on, we can still derive somewhat of answer from the fact that peatlands does have a large organic N storage in the solid peat, and that some degree of leaching could take place with higher water flow levels (Limpens et al., 2006). This should be reasonable since these peaks indeed correlated with high water flow levels. There was also a strong correlation between DOC/TOC and tot-N (Figure 7).

Why only BAG Site 2Bag and 3Bag showed peaks, and BAG Site 1Bag had none observed, is harder to explain. We would probably need a more detailed description of the catchments and stands connected to these sites. One possibility is that Site 2Bag and 3Bag simply have more well-drained stands than Site 1Bag, and thus leaching through the groundwater to the stream happens more easily.

Another interesting thing to consider is how the peaks of different chemical compounds coincided with peaks of the DOC/TOC. Viewing the resulting peaks seems to give the correlation that all the reference and downstream sites coincided with the DOC/TOC peaks, while most BAG site peaks did not. This further helps rule out water flow as the single explanation for the peaks in the BAG sites and might indicate an effect by the fertilization on the stream water chemistry.

Looking at the time of the fertilizations in correlation to the peaks in the BAG and downstream sites is also an important aspect to further understand the nature and relationship of the peaks. (Of course, this is not relevant for the reference sites as fertilization has not been practised there, though the possibility of mistakes in the application of fertilizers should be kept in mind as a possibility). What was observed in the BAG sites peaks was whether a fertilization had been done in the previous four weeks before the peak appeared in the data. Roughly 47 % of the BAG peaks occurred within four weeks of a fertilization being done in the HYEF, and none of the downstream peaks. Looking further into it, for each separate chemical compound, we can see that the tot-N and NH_4 both only had a single BAG peak within four weeks after fertilization. The NO_2 + NO_3 had five (45 %) of its BAG peaks within four weeks after fertilization. The three downstream peaks that did not occur in the weeks after fertilization. Lastly the PO_4 had no peaks within four weeks after fertilization. Thus, most of these peaks cannot be explained by a fertilization being done within a month before the observations. The tot-N peak occurred the same month as the fertilization, the NH_4 the month after, and the NO_2 + NO_3 peaks all observed the month after fertilization except for one single observation, which showed up the month of the fertilization.

This gives us a better perspective of the effects of the BAG fertilization at Undersvik where 100 kg N ha^{-1} were fertilized in the 1st year, and 150 kg N ha^{-1} in the 2nd year. It does not come as a surprise that some degree of an effect would be detectable after this silvicultural measure, when a deposition of just 10 kg N ha^{-1} yr^{-1} is enough to elevate the risk of N leaching, and 25 kg ha^{-1} yr^{-1} has been mentioned to be the threshold for a significant increase in N leaching (Lundin and Nilsson, 2021). The puzzling thing about the previous statement though, is why most peaks cannot be connected to the fertilizations in the same manner. We must also consider that the statistical tests did not show statistical significance. Thus, even though these peaks exist, they probably are not an indication of any longer term changes, with the except of the inorganic N peaks. Many of the non-nitrate peaks could be a result of other natural factors such as precipitation and temperature. These sites also might have already had a big deficiency in N availability, and more N could be applied without leaching out into the water streams. As figure 4 below illustrates, where the fertilization applied in the Undersvik HYEF have been done in this manner and with an amount of N that would represent the green area in the figure. This is the area that N fertilization schemes should aim for, as this is where high forest production is combined with a low N leakage (Laudon et al., 2011b).

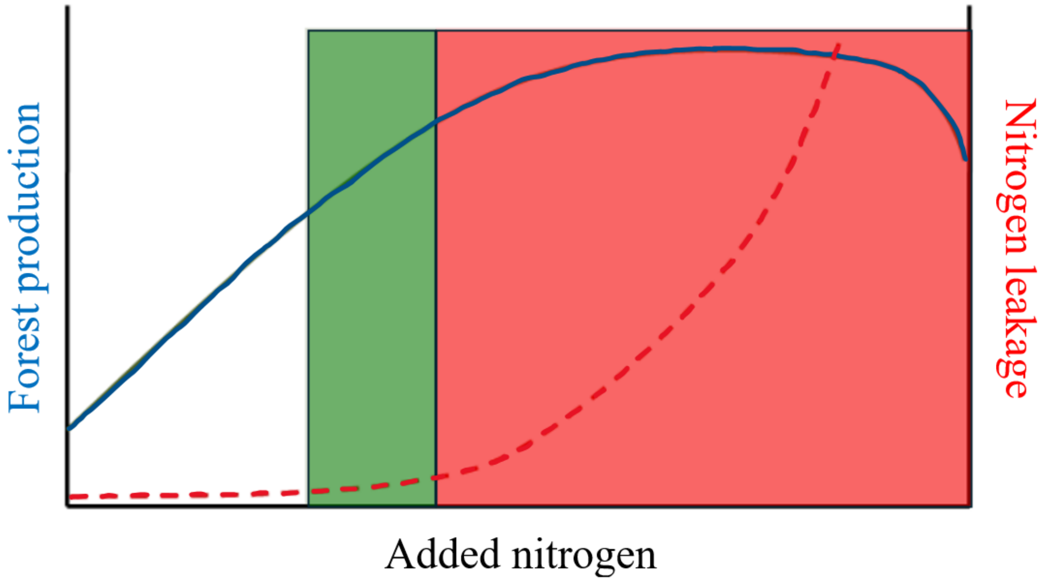

Figure 10. Model developed to elucidate the influence of N addition on both forest production (depicted by the blue line) and N leakage (depicted by the red dotted line). Elevating fertilization rates leads to increased biomass production until tree growth plateaus, driven by constraints from various factors. Initially, the added N is retained within forest ecosystems. However, as time progresses, these systems reach a saturation point where the supply of mineral N exceeds the demand of plants and microbes, resulting in leaching of N from soils into groundwater and subsequently streams. The green area in the model is what should be aimed for when practising N fertilization, as this is where the optimal forest production in combination with the lowest N is obtained. Adapted model from Laudon et al. (2011b).

The chemical compounds that showed up most frequently as peaks within 4 weeks after fertilization, was NO_2 + NO_3. This is expected, as it has been mentioned as a risk by many previous studies e.g. the paper by Lundin and Nilsson (2021) warning that N fertilization can have adverse effects. Nitrate is particularly prone to leaching to stream water flow. NO_2 + NO_3 are relatively soluble and mobile chemical compounds, therefore this is something to expect from well-drained forest soils.

While the appearance of inorganic N peaks already after three years at Undersvik HYEF, it would be of great value to observe how the leaching behaves in the coming 10-20 years, both regarding peaks and annual exports. In a paper published by Moldan et al. (2018), where they studied addition of N to a whole forest ecosystem and observed NO_3 leaching over a time span of 26 years, it was suggested that the added N did indeed not cause a uniform increase when it comes to NO_3 leaching. The authors claim that the ecosystem "stabilized" after 8-10 years of the treatment, that included adding ammonium nitrate (NH_4NO_3) at 40 kg N ha^{-1} $year^{-1}$, somewhat like the experiment at Undersvik. This potentially means that the peaks we observed at Undersvik, might be a phenomenon that only appears in the first 8-10 years of the treatment, but only time will tell whether this is the case.

4.2 Has BAG treatment had less of an effect compared to conventional fertilization?

An important question is whether BAG fertilization treatment has more or less of an effect on the stream water chemistry, compared to the standard conventional method of fertilization. One way to try to answer this is to compare the data, with data collected from a conventional fertilization, such as in the paper “Initial effects of forest N, Ca, Mg and B large-scale fertilization on surface water chemistry and leaching from a catchment in central Sweden” published by Lundin and Nilsson (2014). In this study they compared a fertilized catchment Risfallet (RF) and a control catchment Gussetjärn (GT), where both were in the boreal region of central Sweden. Catchment sizes was 45 ha for RF and 83 ha for GT. GT was mainly dominated by trees more than 100 years old, with younger forest approximated to be about 60-year-old on 20% of the area, whereas the RF catchment had an average age of 35 years, mainly pine (*Pinus sylvestris*) dominated. This study also fertilized with nutrients other than N. The main thing to focus on here is that they fertilized the RF catchment with 150 kg of N. In the same manner as with the Undersvik data, they conducted t-tests for statistical testing in this study.

They found a statistically significant difference for both NO_3-N and tot-N, where the NO_3-N gave more evidence for being statistically significant. However, no statistically significant difference was found for the NH_4-N. Referring to Table 2 and Table 3 in the results section, no significant differences in either the $NO_2 + NO_3$ or tot-N was found, for either the concentrations or the exports. I interpret this as potential evidence for the BAG fertilization method being superior to the conventional method of fertilization when it comes to minimizing the leaching of N and effect on stream water chemistry, at least after the first several years. Of course, it will only be after more years of observing BAG before this question can be satisfactorily answered.

A potential explanation of the results could likely be the timing, or the point of time in the individual stands rotation cycle where the fertilization took place. This determines how susceptible the trees in the stand are to being able to take up the N that is available, i.e. the N demand. Nutrient uptake and demand is highest in young stands, including the uptake and demand for N, which is considered the primarily limiting nutrient for trees in boreal forests (Bergh and Hedwall, 2013). This can be shown in Figure 5 below, where the nutrient uptake is high and steadily increasing until a point in the stand age after which demand decreases. Therefore, a higher risk of leaching and consequently altering the water chemistry in nearby streams is more probable when fertilizing older forests compared to younger ones.

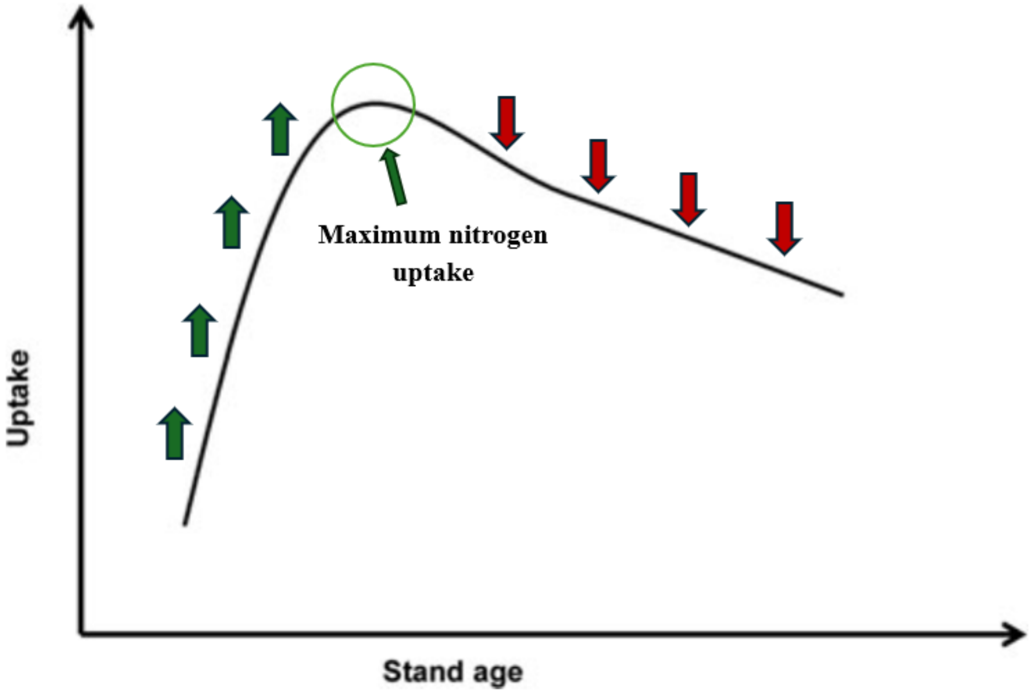

Figure 11. Graph illustrating the relationship regarding nutrient uptake and stand age. Green arrows indicating increase in N uptake, and red arrows indicating decrease in N uptake. Adapted from Bergh and Hedwall (2013).

Another factor to consider with comparing Undersvik HYEF and Risfallet is the data for the Undersvik and Risfallet sites before fertilization. Undersvik had nine months of data from before fertilization, while Risfallet data was collected for 24 years before the fertilization in the RF Site (Lundin and Nilsson, 2014). Therefore, differences before and after fertilization will be easier to observe at Risfallet, and other factors affecting the water chemistry are easier to rule out. Another thing to keep in mind is the size of the catchments, as those from the RF and GT sites were significantly larger than the ones at the Undersvik experiment park.

Further, to have a complete understanding of the comparison of the different fertilization method effects, a closer look on the harvesting at the end of the different stands rotation periods will be crucial. The major N leaching might not occur during the fertilization or in the following decades. Instead it might be, during the harvesting at the end of the rotation period, which is known as a time for increased nutrient leaching (Kreutzweiser et al., 2008). As discussed in the paper by Futter et al. (2010) runoff often increases several years following final felling. They focus mainly on the NO_3 leaching and its relationship when final felling is practiced. Nitrate is also the chemical compound that we observed as peaks from BAG sites at Undersvik HYEF. Therefore, it will be interesting to see how the stream water chemistry is affected during and after harvest.

4.3 Can BAG be seen as a plausible substitute to conventional fertilization in Swedish forestry?

Using the data from Undersvik, is it possible to tell whether the BAG fertilization is a plausible and perhaps superior substitute to the conventional method of fertilization in Swedish forestry? I would like to say there is no definitive answer to that yet, but there are some hints.

There is an indication to some degree that the BAG fertilization has less of an effect on the stream water chemistry because of less N leaching, when directly compared to conventional fertilization experiments. And this in addition to the statistical testing not indicating any significant differences when testing the Undersvik HYEF fertilized and reference sites against each other after the first two fertilizations. However, there are still uncertainties that need to be answered. Firstly, the 3 years of data could not possibly be enough to tell how the stream water chemistry will develop during the stand development until final harvest, and then in the years after harvest. The study must continue for a longer period, as we now only observe a small percentage of the rotation cycle of the stands. What, for example, as mentioned earlier happens during and after harvesting if BAG fertilization were to be used for that long of a period? Is there a potential risk for saturation in the soil, so that a large increase in N nutrient leaching to nearby streams might occur? Or will the forest ecosystem “stabilize” after the first 8-10 years of the treatment such as in the Moldan et al. (2018) paper? And will the isolated peaks of inorganic N from BAG sites become more frequent as more N is added to the soil by further fertilization as planned for the BAG concept? Or will something else unfold? Another consideration is the need to look at a range of different soils and climate settings when one wants to assess the use of BAG on a national level.

Finally, when considering whether BAG method is a good substitute for conventional forest fertilization, there is a need to look at the larger scale of things from other perspectives. Even if BAG proves superior regarding mitigation of nutrient leaching and effects on streams, is it preferable in other aspects? These other aspects include forest production and economical profitability, as well as the effects on biodiversity in the forest. We would want forest owners and companies to genuinely view BAG as the more viable option for fertilization from a variety of perspectives. These other aspects will need to be assessed when exploring BAG fertilization for forestry in Sweden on a national level.

5. Conclusion

The statistical testing did not lead to any evidence indicating a big effect on the stream water chemistry from the BAG treatment. This may be because I: This method of fertilization does not have a large or significant effect on the stream water chemistry, or II; The effect of the BAG fertilization treatment on the stream water chemistry is yet to be seen, as too few fertilizations have been executed and not enough time has passed. Peaks and extreme values from the time series gave some insight and evidence for some effect taking place due to the BAG treatment. This could be derived from the correlation with the waterflow, as the reference site peaks coincided with periods of high water flow, and BAG sites with low water flow. No surprise that the fertilization would show some kind of imprint, as lower amounts of N have shown to elevate the risk of leaching than what was applied at Undersvik so far, though we must consider that the statistical tests did not show any statistical significance. Even if these peaks have occurred, they probably are not an indication of any long term changes, at least yet. The Undersvik project might be a good example of maximum forest production in combination with minimum N leakage. When comparing similarly done studies on conventional fertilization, it seems to give the indication that BAG is superior when it comes to mitigation of N leakage, but too little time has passed for this to be satisfactorily answered. Questions like what happens at the end of the rotation cycle during harvest after decades of BAG treatment still need to be investigated. Whether BAG treatment as a plausible substitute to conventional fertilization on a national level is hard to answer at this moment. Thus far we could say that what we have seen from Undersvik is a good start with a positive outlook. However, more time to follow the effects of BAG at Undersvik is needed before the contribution of this study to understanding the feasibility of BAG is clear. Furthermore, we need to look at other perspectives and aspects besides water quality that are relevant for this question. Does it contribute enough to forest production and profitability to be viable in economic terms alone? And are the effects on biodiversity, recreation and other ecosystem services acceptable for forest owners, companies and society as a whole to view BAG as beneficial? Is it the better option in many other regards besides nutrient leaching to streams?

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Appendix 1

Table 1.1. Total annual export of PO_4 for the sampling period in kg and kg/ha

	Site 1D	Site 2D	Site 3D	Site 1Bag	Site 2Bag	Site 3Bag	Site 1C	Site 2C	Site 3C
annual export 2020 aug 11-dec 31 (kg)	11.3	6.82	5.41	1.07	0.46	0.19	0.36	0.41	0
annual export 2020 aug 11-dec 31 (kg/ha)	0.01	0.004	0.005	0.02	0.005	0.1	0.01	0.01	0
annual export 2021 (kg)	32.4	20.1	17.2	2.29	1.09	0.41	1.00	1.15	2.30
annual export 2021 (kg/ha)	0.02	0.01	0.02	0.04	0.01	0.01	0.04	0.02	0.02
annual export 2022 (kg)	25.4	16.1	13.9	1.74	0.77	0.20	0.65	0.95	2.09
annual export 2022 (kg/ha)	0.01	0.01	0.01	0.03	0.01	0.01	0.02	0.02	0.02
annual export 2023 jan 01-aug 14 (kg)	28.9	19.7	12.1	1.60	0.58	0.19	0.50	0.84	2.00
annual export 2023 (kg/ha)	0.02	0.01	0.01	0.03	0.01	0.01	0.02	0.02	0.02

Table 1.2. Total annual export of DOC/TOC for the sampling period in kg and kg/ha.

	Site 1D	Site 2D	Site 3D	Site 1Bag	Site 2Bag	Site 3Bag	Site 1C	Site 2C	Site 3C
annual export 2020 aug 11-dec 31 (kg)	62569	46178	32484.	3094	3504	1124	3638	2601	0
annual export 2020 aug 11-dec 31 (kg/ha)	32.0	30.1	28.6	49.4	36.3	37.8	130.0	51.4	0
annual export 2021 (kg)	193774	125418	89782	6318	9402	2813	8018	6140	14100
annual export 2021 (kg/ha)	99.0	81.7	78.9	101	97.3	94.7	286	122	105
annual export 2022 (kg)	96521	75937	54757	4459	4928	1577	4589	3872	9498
annual export 2022 (kg/ha)	49.3	49.5	48.1	71.2	51.0	53.1	163.9	76.6	70.7

annual export 2023 jan 01-aug 14 (kg)	173582	131382	93459	6034	8293	2327	6801	5504	13986
annual export 2023 (kg/ha)	88.7	85.6	82.1	96.3	85.8	78.3	242.9	108.9	104.1

Table 1.3. Total annual export of tot-N for the sampling period in kg and kg/ha.

	Site 1D	Site 2D	Site 3D	Site 1Bag	Site 2Bag	Site 3Bag	Site 1C	Site 2C	Site 3C
annual export 2020 aug 11-dec 31 (kg)	1273	908	642	47.5	68.3	20.9	64.3	44.7	0
annual export 2020 aug 11-dec 31 (kg/ha)	0.65	0.59	0.56	0.76	0.71	0.70	2.3	0.88	0
annual export 2021 (kg)	4067	2491	1795	101	186	71.4	132	114	269
annual export 2021 (kg/ha)	2.08	1.62	1.58	1.61	1.92	2.40	4.73	2.25	2.01
annual export 2022 (kg)	2307	1821	1240	81.1	142	89.2	82.3	81.5	201
annual export 2022 (kg/ha)	1.18	1.19	1.09	1.29	1.47	3.00	2.94	1.61	1.50
annual export 2023 jan 01-aug 14 (kg)	3991	2919	2051	109	176	57.1	127	110	283
annual export 2023 (kg/ha)	2.04	1.90	1.80	1.74	1.82	1.92	4.53	2.17	2.11

Table 1.4. Total annual export of NH_4 for the sampling period in kg and kg/ha.

	Site 1D	Site 2D	Site 3D	Site 1Bag	Site 2Bag	Site 3Bag	Site 1C	Site 2C	Site 3C
annual export 2020 aug 11-dec 31 (kg)	25.6	17.0	11.6	1.10	2.59	0.27	0.88	0.93	0
annual export 2020 aug 11-dec 31 (kg/ha)	0.01	0.01	0.01	0.02	0.03	0.01	0.03	0.02	0
annual export 2021 (kg)	82.7	45.4	31.3	2.73	4.93	0.80	2.18	2.51	4.91
annual export 2021 (kg/ha)	0.04	0.03	0.03	0.04	0.05	0.03	0.08	0.05	0.04
annual export 2022 (kg)	77.8	58.6	39.2	2.23	5.56	6.03	1.23	2.39	6.01
annual export 2022 (kg/ha)	0.04	0.04	0.03	0.04	0.06	0.20	0.04	0.05	0.05

annual export 2023 jan 01-aug 14 (kg)	86.9	59.5	49.9	2.39	3.71	0.95	1.75	2.59	5.38
annual export 2023 (kg/ha)	0.04	0.04	0.04	0.04	0.04	0.03	0.06	0.05	0.04

Table 1.5. Total annual export of NO_2 + NO_3 for the sampling period in kg and kg/ha.

	Site 1D	Site 2D	Site 3D	Site 1Bag	Site 2Bag	Site 3Bag	Site 1C	Site 2C	Site 3C
annual export 2020 aug 11-dec 31 (kg)	88.9	55.7	48.3	0.87	1.64	0.30	0.69	1.81	0
annual export 2020 aug 11-dec 31 (kg/ha)	0.05	0.04	0.04	0.01	0.02	0.01	0.03	0.04	0
annual export 2021 (kg)	277	216	169	2.94	15.6	20.7	1.78	5.28	8.99
annual export 2021 (kg/ha)	0.14	0.14	0.15	0.05	0.16	0.70	0.06	0.11	0.07
annual export 2022 (kg)	206	156	114	2.62	33.3	47.5	0.56	3.97	6.28
annual export 2022 (kg/ha)	0.11	0.10	0.10	0.04	0.34	1.60	0.02	0.08	0.05
annual export 2023 jan 01-aug 14 (kg)	282	256	183	3.86	5.66	5.35	1.81	4.01	8.28
annual export 2023 (kg/ha)	0.14	0.17	0.16	0.06	0.06	0.18	0.07	0.08	0.06

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