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Krisjanis Vilcevskis

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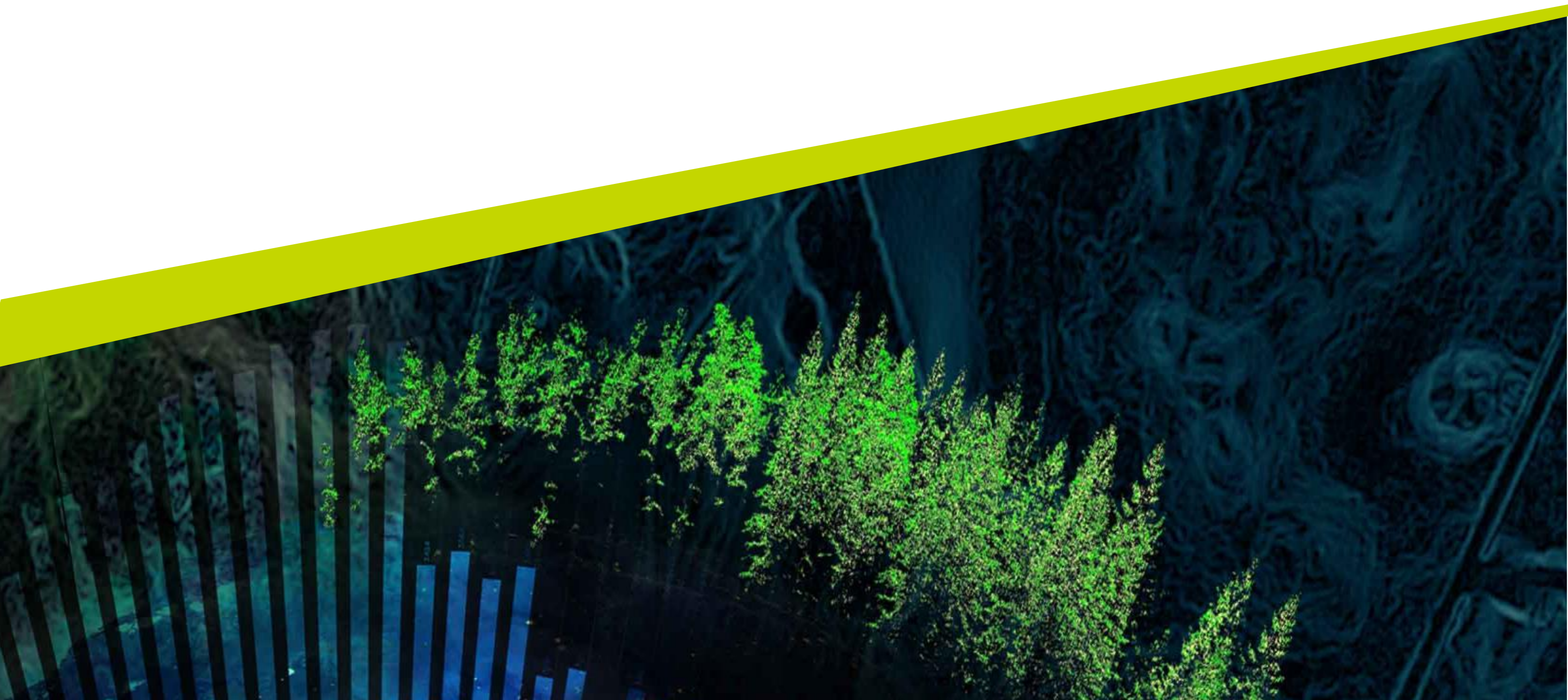

Case study on the effect of intensive fertilization on stream eutrophication at catchment scale

Fallstudie om effekten av intensiv gödsling på övergödning av bäckar i avrinningsskala

Krisjanis Vilcevskis

Supervisor:	**Benjamin Forsmark, Swedish university of agricultural sciences, Southern Swedish Forest Research Centre**
Assistant supervisor:	Mikolaj Lula, Swedish university of agricultural sciences, Southern Swedish Forest Research Centre
Examiner:	Urban Nilsson, Swedish university of agricultural sciences, Southern Swedish Forest Research Centre

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Swedish University of Agricultural Sciences
Faculty of Forest Sciences
Southern Swedish Forest Research Centre

Abstract

One of the ways of mitigating climate change and increasing removal of carbon dioxide from the atmosphere is by providing forests with additional nutrients through fertilization. However, there is a concern that fertilizer nutrients can leach into streams which in turn can elevate risks of eutrophication. This can negatively impact aquatic life in streams, rivers and lakes surrounding the fertilized area. This thesis explores 10-years of intensive nitrogen (N) demand-driven fertilization in a large-scale experiment in southern Sweden. Nitrogen transport trends for the years 2012-2021 were analysed in two catchment areas by collecting streamflow and nutrient concentration measurements. In one of the catchments, young Norway spruce stands was fertilized every second year starting at a mean height of 2-4 m, leading to fertilization of in total one fifth of the area, whereas the other catchment served as an unfertilized control. A range of streamflow estimation methods were applied to acquire accurate N transports estimates. The results revealed that the total N transport was similar in the stream from the control catchment as in the fertilized catchment, with an average annual leaching of 2,04 kg N^{-1} ha^{-1} yr^{-1} and 1,15 kg N^{-1} ha $^{-1}$ yr^{-1}, respectively. The transport of inorganic N increased over time in the fertilized catchment, but not in the control catchment. The seasonal variation of N transport was highest in autumn and winter months, especially in the years of fertilization. Cross-validation of streamflow estimates indicated that the N transport may be underestimated by 8%, however this deviation is relatively minor, and equal for both streams. Thus, the results of this thesis show that the current total N transport in the studied streams is low and similar across catchments, indicating that the risk of eutrophication at catchment scale is relatively minor during the first ten years of an intensive demand-driven forest fertilization program. However, the trend of increasing inorganic N transport over the study period indicate a gradual buildup of N in the soils in the fertilized catchment and warrant further studies, focusing on the long-term effects of climate change and biomass harvest of fertilized stands.

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1. Introduction

In today's world, it has become very evident that the climate is changing (Hegerl et al., 2019, Frol'kis and Kokorin, 2019), and it is happening on a global scale (Stern and Kaufmann, 2014). Growing season has extended in the past few decades while the dormant season like winter is gradually getting shorter (Jiamin et al., 2021, Menzel and Fabian, 1999, Christidis et al., 2007). Also, there is a linear rise of annual average temperature for the past few decades (Twardosz et al., 2021, Jones et al., 1999). Mitigating climate change requires an understanding of, and control over, the exchange of CO_2 between forests and the atmosphere (Anderson-Teixeira et al., 2021). Since forests are a major carbon sink (Harris et al., 2021, Achat et al., 2015) many solutions have been proposed on how forests could remove even more carbon from the atmosphere and offset emissions in the result.

A difference can be made by managing forests in a more sustainable and wiser way, for example, by boosting their sequestration capabilities; wood is an excellent material that binds carbon when being formed, and as mentioned before, this process removes C from the atmosphere. Regarding sustainability this is very important aspect to emphasize and keep in mind when managing forests in the future. Wood can also serve as a substitute for fossil fuels and can be used as a construction material, replacing steel, concrete, and other materials (Bellassen and Luyssaert, 2014). One way of allowing forests to generate more wood and capture more CO_2 is supplying less fertile forests with N fertilizer (Figure 1), and thereby increase their productivity since there is a strong correlation between plant tissue N and critical metabolic processes like photosynthesis and respiration, as well as a control on the amount of soil organic matter (Zaehle et al., 2010) which points to a tightly linked N and carbon cycle (de Vries et al., 2014, Zaehle et al., 2011).

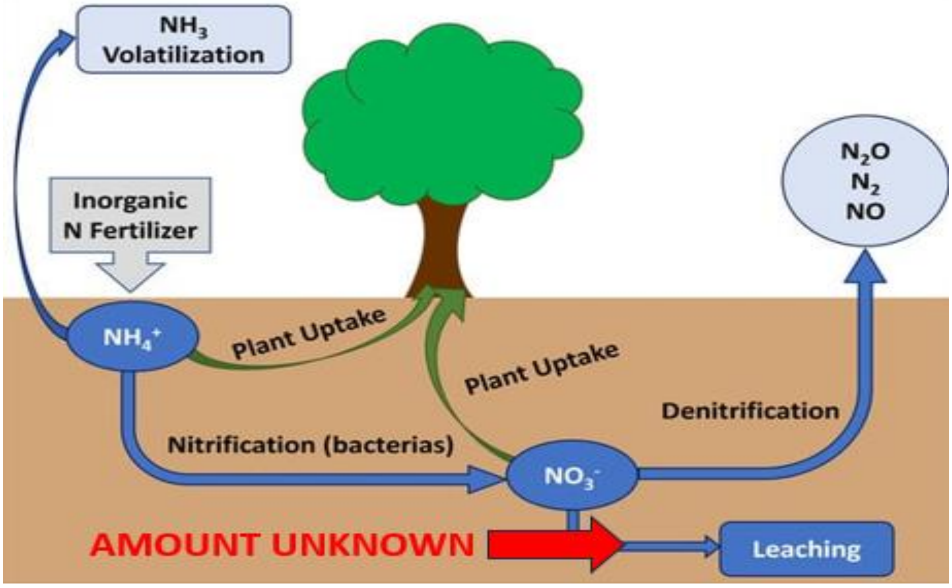

Figure 1. Schematic overview of the key pools and fluxes of the nitrogen cycle in terrestrial ecosystems including forest fertilization. The red arrow indicates the potential environmental implication of forest fertilization target by this study – the unknown amounts of nitrogen lost by leaching and transported in the stream network causing eutrophication in aquatic ecosystems (modified from Brondi et al., 2023)

In traditional forest fertilization, nutrients are supplied predominantly in the mature stand no later than ten years before final harvest, which leads to a temporary increase in stem-wood production by 30-50% over a period of 5 -7 years. However, more intense fertilization regimes can be performed by supplying young forest stands with additional N more frequently and with higher total N supply, and this can lead even up to an 80-300% stem-wood production increase (Hedwall et al., 2010, Pettersson and Högbom, 2004). This can be very beneficial for forest owners who want to manage their forests for production purposes to generate profit from their forests while also removing additional CO_2 from the atmosphere. It is essential to strike a balance between pure production approach and sustainable nature friendly approach. However, not always the forest needs as much added nutrients and it may not even be able to utilize all of the nutrients within a certain amount of time (Ingestad, 1982, Bergh et al., 2005, Bergh et al., 1999). Demand-driven fertilization is the application of fertilizers based on the specific nutrient needs of trees (Ingestad and Lund, 1986) in different forest stands or areas. It aims to optimize the growth and health of trees while minimizing environmental impacts. This is achieved by assessing the current nutrient needs in selected areas by performing foliage nutrient analysis and others. Fertilizers are applied only in a particular section of the forest where it is necessary, essentially where it is lacking, and trees are experiencing low growth rates. In demand-driven fertilization, the fertilizer is applied frequently but in smaller doses than conventional fertilization (Rytter et al., 2003), this results in higher amounts used in demand-driven fertilization throughout a forest stand rotation. Applying fertilizer based on the idea of nutrient flux allows for the provision of fertilizers that match both the natural flux that arises from soil mineralization and the vegetation's capacity for consumption (Fig 1). Under these circumstances, there is a high N consumption rate, and the nutrition-induced feedback on the mineralization rate indicates that fertility could possibly rise with time (Ingestad, 1982). This is the reason why demand-driven fertilization is crucial in forest management, especially, in regard to sustainable management and maintenance of ecological balance within forest ecosystems.

Nonetheless, there are several more major risks that arise when additional N is supplied to forest ecosystems. Those risks are loss of biodiversity, denitrification, and leaching (de Vries et al., 2014, Hedwall et al., 2010, Vitousek et al., 2002). Nitrogen leaching occurs when some forms of N escape the forest through the soil into the groundwater, eventually reaching surface waters where it can cause major disturbances within aquatic ecosystems, although it is a natural part of the N cycle (Figure 1). Nutrient over-enrichment in surrounding ecosystems can cause eutrophication (oxygen depletion, algal blooms) and acidification of water. Eutrophication is especially dangerous because it can heavily impact aquatic life, creating dead zones, fish kills etc. due to low oxygen levels in the water (Bijay and Craswell, 2021, Randall, 2004, Hellsten et al., 2015). The threshold for N regarding risks for freshwater aquatic life is 13 mg L^{-1} for nitrate and 0.06 mg L^{-1} for nitrite. NH_3 (ammonia) concentrations at 0.03 mg N L^{-1} can be potentially toxic to organisms in the short term and concentrations < 0.002 mg L^{-1} can be toxic over the long term (Binkley et al., 1999, Pike and Perrin, 2005). Regarding eutrophication risks a threshold of 1,5 mg N L^{-1} is mentioned in the existing literature (Forsberg and RydingSo, 1980).

This study aims to investigate N leaching into forest water streams in young forest stands where demand driven fertilization experiments have been carried out in southern Sweden in Asa high yield experimental forest, and the current hypothesis is that total N transport in forest water streams increases with increased applied fertilizer amounts. This includes both – organic and inorganic N since both forms can aid eutrophication processes. In Asa HYEF fertilization programme is designed to be intensive in order to see the possible effects on the environment and tree growth. It is essential to assess how much N possibly is leached into forest water streams to see how it could possibly affect the surrounding environment. To investigate leaching, which involves the movement of chemical compounds, organic and inorganic compounds from catchments, it is required to determine the water discharge (stream flow) in the streams. Stream flow speed can be measured by using a few different methods. This study explores and evaluates these methods and compares them against each other to see how streamflow measurement precision and differences in flow estimates between the methods can alter the result of N transport (leaching) in two selected areas that can be directly compared in terms of N transport and flow estimate results. It is crucial to compare fertilized areas with non-fertilized areas in regard to leaching and streamflow estimation methods to make any conclusions related to the effects of fertilizer application in these forested areas and how hydrology affects the result.

2. Materials and methods

2.1. Study area

The Asa research station, together with the Asa experimental forest and Asa high-yield experimental forest (Asa HYEF), is situated in southern Sweden. The combined study sites include a total of 2,700 hectares of forest land, ranging in elevation from 165 to 285 meters above sea level. Study area experiences temperate climate and is located in the temperate forest ecological zone. The mean annual temperature recorded during the climatic reference period of 1991-2020 was 6.5 °C, while the average annual precipitation reported during the same time amounted to 737 mm. The average accumulated temperature over the vegetative period is 1,417 degree-days, and the duration of the growing season, defined by a threshold temperature of +5°C, is 201 days.

The establishment of the Asa research station and Asa HYEF was prompted by a growing interest in conducting forestry research in southern Sweden. The first research initiatives mostly focused on forest regeneration, such as studying the impact of pine weevil damage, frost damages, and browsing by roe deer. The Asa HYEF was constructed in 2009. The dominant tree species in the HYEF is Norway spruce, accounting for 72% of the total species distribution. Scots pine makes up 23% whereas broadleaved trees, on the other hand, represent just 5% of the total. The objective is to assess the capacity and impact of intensive forestry on a larger scale within the landscape. The objective is to achieve a 50% increase in biomass output by the year 2050 via the use of intensive forest management practices, while concurrently monitoring and assessing the environmental consequences.

Asa HYEF employs various silvicultural practices and management programs to enhance growth, such as demand-driven fertilization of young spruce stands, utilization of introduced fast-growing tree species like hybrid larch and lodgepole pine, adoption of genetically improved seeds and seedlings, and enhanced regeneration techniques. A permanent network of circular sample sites was set up to measure and track changes in productivity and vegetation.

For this case study two catchment areas were chosen to practically perform the hydrological measurements and compare a range of methods in the selected streams and therefore calculate N transport amounts. The nature of this research is to test fertilization at an environmentally and silviculturally relevant scale, and statistical testing of the hypothesis is not performed.

2.2. Fertilization treatment

A major management strategy to enhance growth and yield in the Asa HYEF is intensive fertilization of young Norway spruce. The method is a local adaptation of demand-driven fertilization program (Bergh et al., 2008), which is tailored to the unique requirements of each spruce stand in the Asa HYEF. Briefly, fertilization is started when the young spruce forest reaches an average height of 2-4 meters and is repeated every second year until crown closure, and thereafter every 7 to 10 years. Fertilization will not be applied in the last seven years before clear-cutting. The fertilizer blend and application rate are adjusted to meet the current nutrient requirements. Needles are sampled and analysed before each application of fertilizer. The first treatment typically consists only of a common forest N fertilizer product Skog-CAN (ammonium nitrate). Subsequent applications typically use other products that also includes phosphorus, potassium and other elements to correct for secondary limitations (Harpole et al., 2011). An examination of needles revealed a deficiency of many nutrients, notably phosphorus, over the whole region. Fertilizer is applied by a helicopter. In total, 750 kg N ha^{-1} had been added to ~17% of the total catchment area 17 during the study period 2012-2021, which corresponds with ~75 kg N ha^{-1} yr^{-1} fertilization regime. This amount is unique for this particular catchment.

Organic and inorganic matter transfer is studied in catchment regions with fertilized stands and in streams without fertilized areas within their catchments to compare fertilization effects on water quality etc. Two catchment areas were selected for in-depth analysis in this study. Number 2 and 17 (Figure 2), one of them being frequently fertilized and the other one serving as a control (Table 1). These two catchments were selected based on spatial proximity and relative similarity in catchment and forest composition (Table 1). Fertilization was carried out every second year in the period 2012-2021. Even years starting at 2012 being fertilized and odd years not.

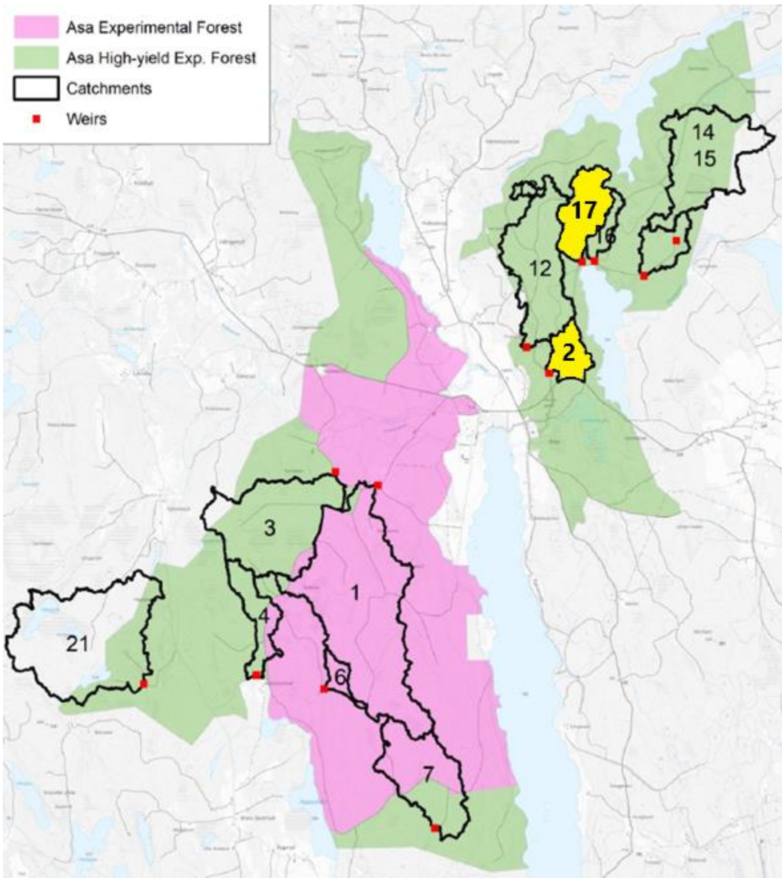

Figure 2. Map of the experimental forests, catchments, and water samplings points (weirs) at the Asa HYEF. In yellow color control catchment 2 and fertilized catchment 17 are highlighted (Ola Langvall et al., 2022; unpublished report).

Table 1. Characteristics of the two catchments studied in this thesis. The catchments were selected out of a total of 12 catchments in the Asa high-yield experimental forest (HYEF) based on proximity, similarity in soil and forest cover, and completeness of hydrological data record. Fertilization of young Norway spruce stands started in 2012 and is repeated every second year including 2021 as the latest year covered in this study.

	Catchment 2 (control)	**Catchment 17 (fertilized)**
Area, ha	22,7	42,6
Standing volume, m^3 ha^{-1}	236	172
Age	56	42
Site index (H100)	29	23
Fertilized area, % of catchment area	0	16,9 (7,2 ha)
Fertilizer applied 2012-2021, kg N ha^{-1}	0	750

2.3. Stream nitrogen transport measurements

To estimate the transport of N in the stream network historical records of streamwater N concentrations (µg/L) with streamflow measurements (L/s) were combined.

To acquire concentrations water sampling was done regularly every month since 2012 in both catchments: 2 (control) and 17 (fertilized). In total 23 values were analyzed from these water samples but for this particular study 3 of them were essential:

- ammonium (µg/l)
- nitrite and nitrate (µg/l)
- total N (µg/l).

Ammonium (NH_4), nitrite (NO_2), nitrate (NO_3) together form the inorganic part of the total N, which is an essential value to look into when assessing the possible effects of fertilization since it could lead to increased inorganic N transport within the water streams when compared to the control area.

Streamflow was estimated using a range of methods. Weirs were constructed at each sample location to enable continuous monitoring of water flow. Water discharge may be measured by measuring the water level in the pool above the prescribed overflow. The equation below is used to measure flow speed. This equation is used for sensor water stage level and manual water level measuring methods.

1) $Q = \frac{8}{15} \cdot \mu \cdot h^{2.5} \cdot \sqrt{2 \cdot g}$

Q = volumetric flow rate (m3 s-1)
µ = flow correction factor (ca 0,6)
h = height of the water above the bottom of the V-notch (m)
g = acceleration due to gravitation (9.81 m s-2)

Water stage level method (*stage predicted*)

The water level is regularly monitored using submerged pressure sensors. Level TROLL 700 loggers were used from July 2012 to 2021. The loggers recorded water temperature and pressure every minute and stored an hourly average. Data was transmitted over a gateway to the internet, allowing for almost real-time monitoring of values. Seven sensors can transmit data, but the other sensors are unable to connect to the gateway owing to extensive vegetation and/or topography. Data from these sensors can only be retrieved by collecting the SD cards. Streamflow can also be manually measured at the weirs by measuring the necessary height values listed in equation 1. During each sample, the distance from the top of the weir to the water surface is measured on both sides. It is also observed if water flow is affected by trash, leaves, ice, etc. Streamflow measurements acquired by this method is used to create rating curves to calibrate/validate *stage predicted* estimates.

Streamflow is calculated using equation 1 and the resulting estimates are coupled up with the measured chemical compound concentration values to get an average transported amount monthly for the period of 2012-2021. This is being done for catchment 2 and 17 separately since catchment 2 is used as a control and has not been fertilized. This way fertilized and non-fertilized areas can be compared regarding N transport in the water streams.

Bucket and salt injection method *(measured)*

Stage predicted flow estimates can also be cross validated using either the "bucket method," the "salt injection method," or both. The first approach involves filling a bucket with water from the weir and measuring the time it takes to reach a certain water level. The second approach involves injecting salt upstream to a measurement point where conductivity is measured, and it is the only way suitable for high flow conditions. The stream must be sufficiently strong to uniformly distribute all salt in the water body for an accurate measurement since the sensors only take readings at one or two spots in the water. Conductivity is converted to salinity concentration by calibrating the sensors with known salt concentrations. The salinity levels above the background are accumulated over time as the water flows past the sensors to determine the flow rate.

Water discharge modelling method

This method uses SMHI S-hype model data that predicts water flow over large areas based on the terrain and other aspects. Stream flow is modelled for every day, which is then used to calculate monthly averages for stream flow. Results acquired from these methods can then be compared to *stage predicted* and *stage corrected* estimates.

2.4. Calculations and statistics

Period N transport was calculated as the product of N concentration and cumulative streamflow. This study is a case study of one pair of catchments, hence regression analysis was chosen to compare the two catchments in terms of annual fluctuations of total N transport amounts. Regression analysis was also performed for the inorganic N transport for both catchments separately to inspect possible transport increase trends over time.

3. Results

Annual nitrogen transport

The total annual N transport in the unfertilized catchment was on average 2,04 kg N ha^{-1} yr^{-1} and varied 3-fold across years, from 1.1 to 3 kg N ha^{-1} yr^{-1}. In the fertilized catchment, the annual transport was on average 1,15 kg N ha^{-1} yr^{-1}, and had a similar variation as the control catchment and a min and max ranging from 0.7 to 1,6 kg N ha^{-1} yr^{-1} (Figure 3a). Across the years, control catchment N transport is higher than in the fertilized catchment within the stream water. The total transported inorganic N amount 2012-2021 in control catchment was 2,48 kg ha^{-1} and 2,74 kg ha^{-1} in fertilized catchment. Annual transport of N was strongly positively correlated (R2 = 0.70) between the catchments and the slope of the linear relationship indicate that the fertilized catchment consistently exported 50% less N than the control catchment (Fig 3b).

Inorganic N transport increased by 0.03 kg ha^{-1} year^{-1} in the fertilized but no increase with time in control. The lowest inorganic N transport values were recorded in 2018 in both streams (Figure 4).

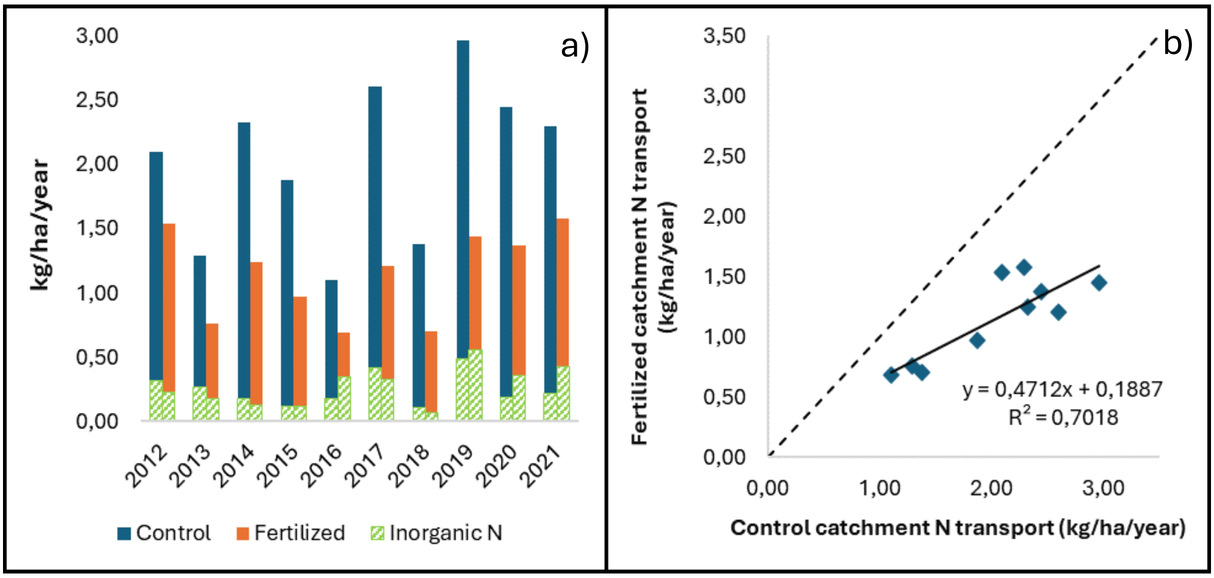

Figure 3. a - annual total nitrogen transport (2012-2021) for unfertilized control catchment (blue) and a fertilized catchment (orange). Transport of inorganic nitrogen is plotted with black and green lines. b - annual total nitrogen transport (2012-2021) in fertilized catchment as a function of an unfertilised catchment. The dashed diagonal line denotes equal nitrogen transport, the solid black line, and the statistics the best fit of a linear regression function.

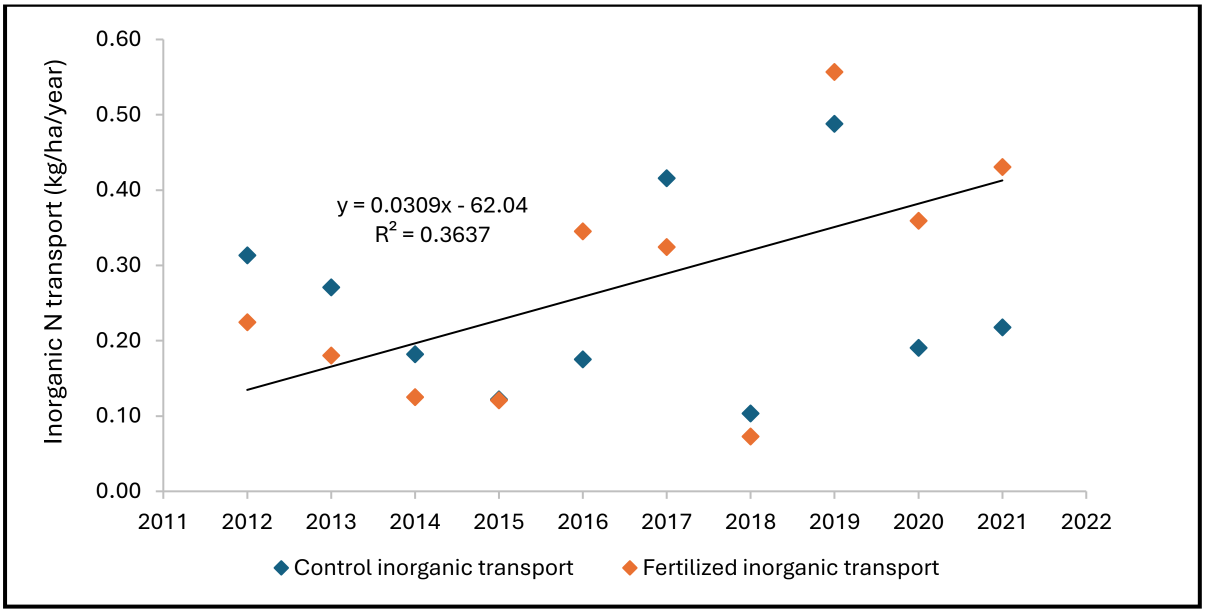

Figure 4. Annual inorganic nitrogen transport (2012-2021) in fertilized and control catchments. The solid black line and the statistics the best fit of a linear regression function. The corresponding fit for the control catchment was R^2 = 0,0018 and not shown.

Seasonal variation in nitrogen transport

Within years, total N transport varied seasonally from peak transport during the winter months, corresponding with peak streamflow, and minimum transport occurring during summer. The mean monthly transport of N was higher in the control than the fertilized catchment. Minimum recorded N transport was 0,0016 kg N ha^{-1} month $^{-1}$ while the maximum was 0,81 kg N ha^{-1} month $^{-1}$ (Figure 5). Streamflow in both catchments peaks during the winter and early spring months and plummets in the summer months. The same trend can be seen in the monthly N transport amounts within the water streams, highest N transport occurring in February (Figure 5). The N transport is highest in winter and autumn months. Control stream shows higher values than fertilized stream. The transport is relatively small in both streams, but there is a significant dispersion of data visible in some of the months, particularly in the winter and autumn season. In the months following fertilization there is an increased N transport in both catchments (Figure 5) and while the total N transport seems to differ between the fertilized and control catchment, inorganic N transport is largely the same in both areas. During a 24-month fertilization cycle it shows how fertilization year corresponds to a calendar year (Figure 6). Fertilization is usually carried out in June, so this is the first month of a fertilization year. One fertilization cycle lasts 2 years because fertilization is carried out every second year as mentioned before. It is visible that both – total N transport and inorganic N transport (kg ha^{-1} $month^{-1}$) - reach their highest values 8 - 9 months after fertilization in both catchments. In the second half of the fertilization cycle total N transport reaches similar heights but inorganic N transport decreases significantly, especially in February when compared to the year of fertilization.

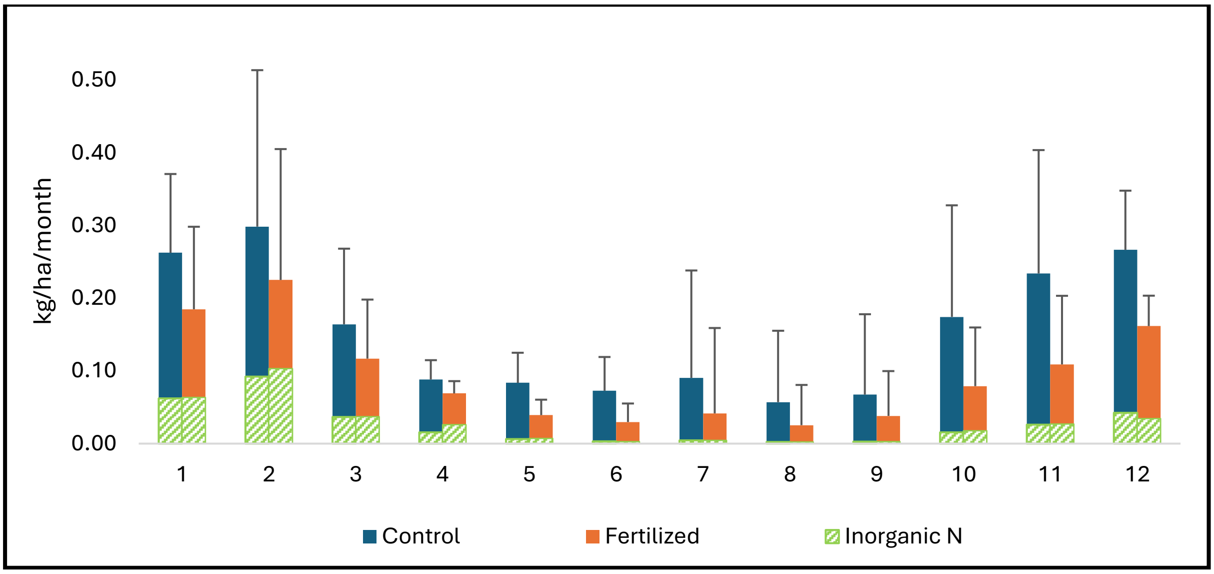

Figure 5. Monthly total nitrogen transport averaged across years (2012-2021) for unfertilized control catchment (blue) and a fertilized catchment (orange). Error bars denote the standard deviation. Transport of inorganic nitrogen is plotted with green hatched bars.

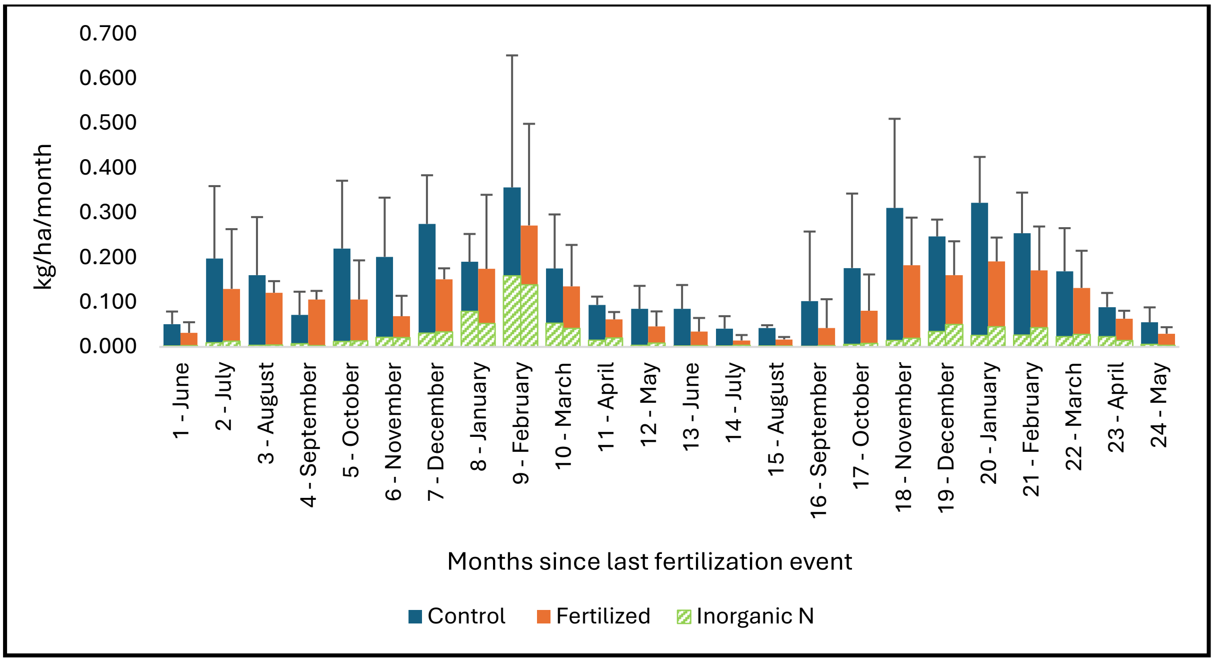

Figure 6. Monthly average total nitrogen transport (2012-2021) in control (blue) and fertilized (orange) catchments and transport of inorganic nitrogen I s plotted with green hatched bars, across the 24 months fertilization cycle. Months since last fertilization event are laid out alongside corresponding calendar month. Interval between fertilization events is usually 24 months.

<u>Comparison of streamflow estimates</u>

The linear regression graph in figure 7a shows that measured streamflow very strongly correlates with the stage predicted flow in both catchments. The manual streamflow measurements verified that the stage estimated streamflow was consistent across a wide range of streamflow values ($R^2 > 0.97$ for linear regression) but the slope was higher than 1, indicating that streamflow has been underestimated more at higher streamflow. The annual flow estimates showed that the underestimation is approximately 8% in both streams. SMHI S-hype modelled annual streamflow estimates (mm yr^{-1}) exceed both the *stage predicted* and the *stage corrected* estimates in both streams (Figure 7b).

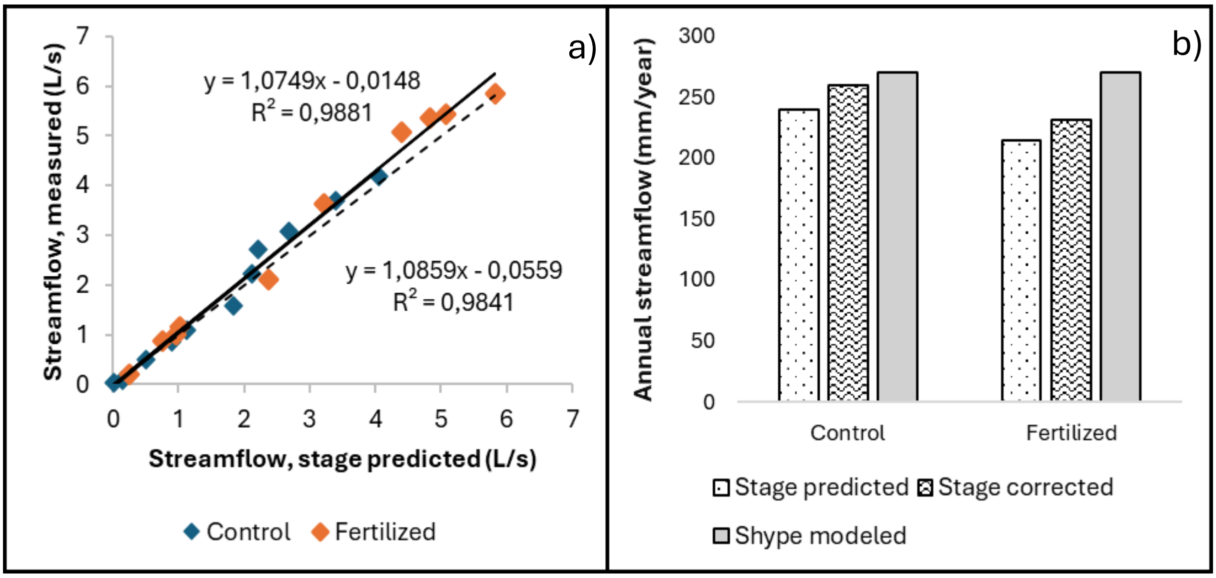

Figure 7. Relationship between streamflow estimated by stage measurements (Equation 1) and estimated by direct measurements using the bucket and salt-dilution method (a), and the annual streamflow estimated using different methods (b). Blue and orange datapoints represent control and fertilized catchment streamflow values, respectively. The dashed diagonal line denotes equal streamflow values, the solid black lines and the statistics the best fit of a linear regression function for each catchment. Annual streamflow was estimated using the stage method, the stage method corrected using the catchment specific coefficients in panel (a), and the local predicted streamflow from the SMHI S-hype model.

4. Discussion

The goal of this thesis was to explore the potential environmental impact of intensive N fertilization on streamwater eutrophication. The leading hypothesis was that a high amount of N addition in a forested catchment will lead to higher organic and inorganic N transport in the stream outlet. To test the hypothesis, N transport in two similar catchments differing mainly in fertilizer application was studied by combining a long-term data series on streamwater N concentration with streamflow estimates.

The measurements did not provide any clear evidence for increased total N transport in the fertilized catchment. Control catchment total N transport values are higher in all years than the fertilized catchment values and N transport in both catchments increases slightly over the span of 10 years (Figure 3). This would suggest that many factors are at play which control the N cycle in these particular forest catchments at the time. Though, inorganic N increase is higher in the fertilized catchment, an increase over time is visible in fertilized catchment and not the control (Figure 4). This is a crucial finding of this study in regard to possible inorganic N transport changes in the future even if at the moment leached amounts are relatively low. In total, ~750 kg N ha^{-1} had been added on roughly one fifth of the catchment area (7,2 ha) over a 10-year period of intense young forest fertilization regime according to the principles of demand-driven fertilization. The experiment is located in an area with a long history of N deposition and relatively high baseline N stocks, which would make the area prone to leaching.

Both streams experience similar trends in transport fluctuations throughout the years, this hints towards a relationship that is based on similar influencing factors (Figure 4). Those could be precipitation patterns, evapotranspiration, deposition etc. Control catchment represents the natural background leaching which is a part of the natural N cycle in forests and is used as a reference point for the fertilized catchment. Therefore, the results do not entirely support the hypothesis of this study, but an increase of the inorganic N transport, although minor at the moment (Figure 4), is something that should be addressed and taken into account..

Nitrogen transport is the periodic product of the N concentration and streamflow and biases in any of these factors could potentially distort the result. Whereas N concentrations are measured in a standardized manner across the two catchments, local variations in stream characteristics can lead to differences in the accuracy of predicting streamflow from stage measurements (Equation 1). Thus, to account for this latter source of errors we measured streamflow and created curves to adjust the streamflow estimated from stage measurements (Figure 7a). Moreover, we also compared our estimates with the S-hype model output (Figure 7b). The result showed highest streamflow estimates for the S-hype model which does not take into account intricacies of individual catchments, such as catchment stand density which is a key driver of evapotranspiration. This results in an offset that exceeds both – *stage predicted,* and *stage corrected* estimates. After correcting N transport with the developed rating curves for each stream, the transport would increase by ~8 % in both streams which in this case does not offset the N amounts as much as expected prior. This result shows that errors or biases in estimating streamflow across catchments are unlikely to mask differences in N transport between catchments.

Another error source is that there is always some deposition (Kanakidou et al., 2016, Gundersen et al., 2011), volatilization and leaching occurring naturally and/or independently from fertilization in forest ecosystems (Pihl Karlsson et al., 2024), and chemical compounds like ammonia, nitrates, nitrites etc. will almost certainly "pollute" streamwater to some extent. The question is whether fertilization will make a significant contribution to N transport in streams besides these factors. This is why the relationship between streamflow values and precipitation is important to understand and address since N transport in streams is very much dependent on the output of the streams. Total and inorganic N transport for both streams is highest in winter and early spring months (Figure 5). This can have several explanations. Firstly, trees do not need N during the dormant period. Secondly there is increased precipitation during the cold and humid months and higher evapotranspiration in the summer months. Thirdly, precipitation has increased in southern Sweden over the last 150 years by about 20%, and this change has appeared only because of an increased winter precipitation while the summer precipitation has not changed (Bengtsson and Rana, 2014).

Supposedly the current demand-driven fertilization regime has not contributed towards a steep increase of transported inorganic N in the fertilized stream as of now. Still, it remains uncertain, where does this added N reside. Based on previous studies in Sweden that inspected carbon sequestration response to fertilization in boreal forests, it is expected that approximately half of the N added to the ecosystem can be recovered either from the soil or trees themselves (Blasko et al., 2022). This suggests that the other half of the added N has escaped the ecosystem either through denitrification, volatilization or leaching (Fig. 1). Applying the same mass balance approach to the fertilized catchment in Asa (Table 1), and assuming that half of the fertilizer N is retained in plants and soils of the fertilized stand, approximately 6 kg N ha^{-1} yr^{-1} could be expected to be released through denitrification, volatilization or leaching. In this particular case study at Asa exactly leaching was inspected, and the total transported inorganic N amounts in stream water tend to increase slightly over a period of 10 years in fertilized catchment. Although, the transported amounts stand at only a maximum of 0,5 kg ha^{-1} yr^{-1} in the year 2019 (Figure 4) brings up a question of where this added N ends up, and if it may be mobilized at a later stage. The same scope of research and analysis has not been replicated at Asa HYEF as in the study mentioned before (Blasko et al., 2022), and the situation may simply be different at this specific location. It might as well be that these particular forest stands in catchment 17 are not N-saturated and the added N is within their biotic demand (Aber et al., 1998, Aber et al., 1989), and the goal of demand-driven fertilization has been reached when inspecting these two particular catchments. These forests stands in the fertilized catchment could also be in a transition process still, and at some point N could become nonlimiting element for the tree growth at which point nitrate leaching could become evident (Galloway et al., 2003). Some studies suggest that in areas of low N deposition retention of N within soil organic matter can reach even up to 95% with additions that go up to 150 kg ha^{-1} yr^{-1} (van Breemen et al., 1982) and this 10 year period could be within a delay period of N release that is being accumulated (Magill et al., 2000). Nitrogen may be flushed out more during the dormant period of the year when trees do not consume as much water and nutrients, and evapotranspiration (ET) is not as active as in the vegetation period, for example. In recent decades the annual ET rates have increased in forests worldwide due to climate change (Wang et al., 2021). This could lead to a significant difference between N transport amounts in dormant and active periods and more pronounced seasonal drought events (Zhang et al., 2009). All of this shows that the situation is affected a lot by many factors and processes and perhaps it would be wise to perform additional analysis (soil N analysis) in these two researched catchments to pinpoint N exchange intricacies more precisely.

Total N transport in the streams of both the control catchment and the fertilized was similar, and relatively low: control – 2,04 kg^{-1} ha^{-1} yr^{-1}, fertilized – 1,15 kg^{-1} ha^{-1} yr^{-1} (Figure 3a), and may not cause concern since the critical threshold of nitrate concentration regarding eutrophication risks in river and stream water is anywhere from 0,3 – 1,5 mg L^{-1} for river and stream water (Xu et al., 2014, Qi et al., 2022, Dodds and Smith, 2016, Forsberg and RydingSo, 1980). Highest inorganic N transport was recorded at ~ 0,5 kg ha^{-1} yr^{-1}. A concentration of 1,5 mg N L^{-1} is equivalent to ~4,3 kg N ha^{-1} yr^{-1} leaching with the current average streamflow estimates in the study area. This shows that the current total N and inorganic N transport in both streams is below levels of environmental concern. Control stream maximum inorganic N concentration was recorded at 0,14 mg L^{-1} and in the fertilized stream it was 0,17 mg L^{-1}. These concentrations are well within the naturally occurring range for unfertilized forest water streams (Dodds, 2007, Nürnberg, 1996). The total transport of inorganic N during 2012-2021 was in the control catchment 2,48 kg ha^{-1}, and 2,74 kg ha^{-1} in the fertilized catchment. It should be noted that the stand structure in the fertilized catchment is different from the control catchment. For example, the site index and age are both lower in the fertilized area. It could also be that the forests within the fertilized catchment utilize added nutrients very well for now but in the future during thinning and/or clear-cuts an increase of possibly stored N can take place (Ring, 1995). This can vary in other areas with different site properties etc. Although, based on the streamflow measuring method comparison and analysis it was concluded that the streamflow has been underestimated at high streamflow in both catchments by ~8% (Fig. 7a). This would suggest that N transport is higher by the same amount, than currently estimated in the study area based solely on the stage predicted streamflow. This is, however, a relatively minor deviation that affects both catchments similarly.

5. Conclusions

It can be concluded that demand-driven N addition in the period of first 10 years has not elevated inorganic and organic N transport above critical loads regarding eutrophication risks in this study of two catchments. Nonetheless, a gradual increase of inorganic N transport is visible in the fertilized area, and over a period of few decades it could possibly reach critical loads regarding eutrophication risks. Differences on monthly average N transport mainly depend on the water cycle, which is partly regulated by precipitation, partly by evapotranspiration. Longer time periods and extreme weather events may cause leaching of stored N later. Longer studies that also inspect amounts of N retained within the study area in the soil are recommended. Assessing whether denitrification and/or volatilization is responsible for possible imbalances in N budget is crucial. N could still be stored in the soil and may be released into the water after precipitation extremes, fellings, or thinnings.

References

ABER, J., MCDOWELL, W., NADELHOFFER, K., MAGILL, A., BERNTSON, G., KAMAKEA, M., MCNULTY, S., CURRIE, W., RUSTAD, L. & FERNANDEZ, I. 1998. Nitrogen Saturation in Temperate Forest Ecosystems: Hypotheses revisited. *BioScience,* 48**,** 921-934.

ABER, J. D., NADELHOFFER, K. J., STEUDLER, P. & MELILLO, J. M. 1989. Nitrogen Saturation in Northern Forest Ecosystems: Excess nitrogen from fossil fuel combustion may stress the biosphere. *BioScience,* 39**,** 378-386.

ACHAT, D. L., FORTIN, M., LANDMANN, G., RINGEVAL, B. & AUGUSTO, L. 2015. Forest soil carbon is threatened by intensive biomass harvesting. *Scientific Reports,* 5**,** 15991.

ANDERSON-TEIXEIRA, K. J., HERRMANN, V., MORGAN, R. B., BOND-LAMBERTY, B., COOK-PATTON, S. C., FERSON, A. E., MULLER-LANDAU, H. C. & WANG, M. M. H. 2021. Carbon cycling in mature and regrowth forests globally. *Environmental Research Letters,* 16**,** 21.

BELLASSEN, V. & LUYSSAERT, S. 2014. Carbon sequestration: Managing forests in uncertain times. *Nature,* 506**,** 153-155.

BERGH, J., LINDER, S. & BERGSTRÖM, J. 2005. Potential production of Norway spruce in Sweden. *Forest Ecology and Management,* 204**,** 1-10.

BERGH, J., LINDER, S., LUNDMARK, T. & ELFVING, B. 1999. The effect of water and nutrient availability on the productivity of Norway spruce in northern and southern Sweden. *Forest Ecology and Management,* 119**,** 51-62.

BIJAY, S. & CRASWELL, E. 2021. Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. *SN Applied Sciences,* 3**,** 518.

BINKLEY, D., BURNHAM, H. & LEE ALLEN, H. 1999. Water quality impacts of forest fertilization with nitrogen and phosphorus. *Forest Ecology and Management,* 121**,** 191-213.

BLASKO, R., FORSMARK, B., GUNDALE, M. J., LIM, H., LUNDMARK, T. & NORDIN, A. 2022. The carbon sequestration response of aboveground biomass and soils to nutrient enrichment in boreal forests depends on baseline site productivity. *Sci Total Environ,* 838**,** 156327.

BRONDI, M., EISA, M., BORTOLETTO-SANTOS, R., DRAPANAUSKAITE, D., REDDINGTON, T., WILLIAMS, C., RIBEIRO, C. & BALTRUSAITIS, J. 2023. Recovering, Stabilizing, and Reusing Nitrogen and Carbon from Nutrient-Containing Liquid Waste as Ammonium Carbonate Fertilizer. *Agriculture,* 13**,** 909.

CHRISTIDIS, N., STOTT, P. A., BROWN, S., KAROLY, D. J. & CAESAR, J. 2007. Human Contribution to the Lengthening of the Growing Season during 1950–99. *Journal of Climate,* 20**,** 5441-5454.

DE VRIES, W., DU, E. Z. & BUTTERBACH-BAHL, K. 2014. Short and long-term impacts of nitrogen deposition on carbon sequestration by forest ecosystems. *Current Opinion in Environmental Sustainability,* 9-10**,** 90-104.

DODDS, W. & SMITH, V. H. 2016. Nitrogen, phosphorus, and eutrophication in streams. 6**,** 155-164.

DODDS, W. K. 2007. Trophic state, eutrophication and nutrient criteria in streams. *Trends in Ecology & Evolution,* 22**,** 669-676.

FORSBERG, C. & RYDINGSO 1980. Eutrophication parameters and trophic state indices in 30 Swedish waste receiving lakes. *Archiv fur Hydrobiologie,* 89**,** 189-207.

FROL'KIS, V. A. & KOKORIN, A. M. 2019. The Influence of the Internal Structure of Particles on Optical Properties of Stratospheric Aerosol, Radiative Forcing, and Global Annual Average Temperature. *Atmospheric and Oceanic Optics,* 32**,** 306-315.

GALLOWAY, J. N., ABER, J. D., ERISMAN, J. W., SEITZINGER, S. P., HOWARTH, R. W., COWLING, E. B. & COSBY, B. J. 2003. The Nitrogen Cascade. *BioScience,* 53**,** 341-356.

GUNDERSEN, P., SCHMIDT, I. & RAULUND-RASMUSSEN, K. 2011. Leaching of nitrate from temperate forests - Effects of air pollution and forest management. *Environmental Reviews,* 14**,** 1-57.

HARPOLE, W., NGAI, J., CLELAND, E., SEABLOOM, E., BORER, E., BRACKEN, M., ELSER, J., GRUNER, D., HILLEBRAND, H., SHURIN, J. & SMITH, J. 2011. Nutrient co-limitation of primary producer communities. *Ecology letters,* 14**,** 852-62.

HARRIS, N. L., GIBBS, D. A., BACCINI, A., BIRDSEY, R. A., DE BRUIN, S., FARINA, M., FATOYINBO, L., HANSEN, M. C., HEROLD, M., HOUGHTON, R. A., POTAPOV, P. V., SUAREZ, D. R., ROMAN-CUESTA, R. M., SAATCHI, S. S., SLAY, C. M., TURUBANOVA, S. A. & TYUKAVINA, A. 2021. Global maps of twenty-first century forest carbon fluxes. *Nature Climate Change,* 11**,** 234-240.

HEDWALL, P. O., NORDIN, A., BRUNET, J. & BERGH, J. 2010. Compositional changes of forest-floor vegetation in young stands of Norway spruce as an effect of repeated fertilisation. *Forest Ecology and Management,* 259**,** 2418-2425.

HEGERL, G. C., BRÖNNIMANN, S., COWAN, T., FRIEDMAN, A. R., HAWKINS, E., ILES, C., MÜLLER, W., SCHURER, A. & UNDORF, S. 2019. Causes of climate change over the historical record. *Environmental Research Letters,* 14**,** 123006.

HELLSTEN, S., STADMARK, J., PIHL KARLSSON, G., KARLSSON, P. E. & AKSELSSON, C. 2015. Increased concentrations of nitrate in forest soil water after windthrow in southern Sweden. *Forest Ecology and Management,* 356**,** 234-242.

INGESTAD, T. 1982. Relative addition rate and external concentration; Driving variables used in plant nutrition research. *Plant, Cell & Environment,* 5**,** 443-453.

INGESTAD, T. & LUND, A. B. 1986. Theory and techniques for steady state mineral nutrition and growth of plants. *Scandinavian Journal of Forest Research,* 1**,** 439-453.

JIAMIN, W., GUAN, Y., WU, L., GUAN, X., CAI, W., HUANG, J., DONG, W. & ZHANG, B. 2021. Changing Lengths of the Four Seasons by Global Warming. *Geophysical Research Letters,* 48.

JONES, P. D., NEW, M., PARKER, D. E., MARTIN, S. & RIGOR, I. G. 1999. Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics,* 37**,** 173-199.

KANAKIDOU, M., MYRIOKEFALITAKIS, S., DASKALAKIS, N., FANOURGAKIS, G., NENES, A., BAKER, A. R., TSIGARIDIS, K. & MIHALOPOULOS, N. 2016. Past, Present, and Future Atmospheric Nitrogen Deposition. *Journal of the Atmospheric Sciences,* 73**,** 2039-2047.

MAGILL, A., ABER, J., BERNTSON, G., MCDOWELL, W., NADELHOFFER, K., MELILLO, J. & STEUDLER, P. 2000. Long-Term Nitrogen Additions and Nitrogen Saturation in Two Temperate Forests. *Ecosystems,* 3**,** 238-253.

MENZEL, A. & FABIAN, P. 1999. Growing season extended in Europe. *Nature,* 397**,** 659-659.

NÜRNBERG, G. K. 1996. Trophic State of Clear and Colored, Soft- and Hardwater Lakes with Special Consideration of Nutrients, Anoxia, Phytoplankton and Fish. *Lake and Reservoir Management,* 12**,** 432-447.

PETTERSSON, F. & HÖGBOM, L. 2004. Long-term Growth Effects Following Forest Nitrogen Fertilization in Pinus sylvestris and Picea abies Stands in Sweden. *Scandinavian Journal of Forest Research - SCAND J FOREST RES,* 19**,** 339-347.

PIKE, R. & PERRIN, C. 2005. Effects of Forest Fertilization on Water Quality. *Streamline Watershed Management Bulletin,* 9.

QI, J., DENG, L., SONG, Y., QI, W. & HU, C. 2022. Nutrient Thresholds Required to Control Eutrophication: Does It Work for Natural Alkaline Lakes? *Water,* 14**,** 2674.

RANDALL, C. W. 2004. The environmental, economic and societal consequences of inadequate nitrogen pollution controls. *Water Science and Technology,* 49**,** 23-33.

RING, E. 1995. Nitrogen leaching before and after clear-felling of fertilised experimental plots in a Pinus sylvestris stand in central Sweden. *Forest Ecology and Management,* 72**,** 151-166.

RYTTER, L., ERICSSON, T. & RYTTER, R.-M. 2003. Effects of Demand-driven Fertilization on Nutrient Use, Root:Plant Ratio and Field Performance of Betula pendula and Picea abies. *Scandinavian Journal of Forest Research,* 18**,** 401-415.

STERN, D. I. & KAUFMANN, R. K. 2014. Anthropogenic and natural causes of climate change. *Climatic Change,* 122**,** 257-269.

TWARDOSZ, R., WALANUS, A. & GUZIK, I. 2021. Warming in Europe: Recent Trends in Annual and Seasonal temperatures. *Pure and Applied Geophysics,* 178**,** 4021-4032.

VAN BREEMEN, N., BURROUGH, P. A., VELTHORST, E. J., VAN DOBBEN, H. F., DE WIT, T., RIDDER, T. B. & REIJNDERS, H. F. R. 1982. Soil acidification from atmospheric ammonium sulphate in forest canopy throughfall. *Nature,* 299**,** 548-550.

VITOUSEK, P. M., CASSMAN, K., CLEVELAND, C., CREWS, T., FIELD, C. B., GRIMM, N. B., HOWARTH, R. W., MARINO, R., MARTINELLI, L., RASTETTER, E. B. & SPRENT, J. I. 2002. Towards an Ecological Understanding of Biological Nitrogen Fixation. *Biogeochemistry,* 57/58**,** 1-45.

WANG, T., ZHANG, H., ZHAO, J., GUO, X., XIONG, T. & WU, R. 2021. Shifting Contribution of Climatic Constraints on Evapotranspiration in the Boreal Forest. *Earth's Future,* 9**,** e2021EF002104.

XU, Z., ZHANG, X., XIE, J., YUAN, G., TANG, X., SUN, X. & YU, G. 2014. Total nitrogen concentrations in surface water of typical agro- and forest ecosystems in China, 2004-2009. *PLoS One,* 9**,** e92850.

ZAEHLE, S., CIAIS, P., FRIEND, A. D. & PRIEUR, V. 2011. Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions. *Nature Geoscience,* 4**,** 601-605.

ZAEHLE, S., FRIEND, A. D., FRIEDLINGSTEIN, P., DENTENER, F., PEYLIN, P. & SCHULZ, M. 2010. Carbon and nitrogen cycle dynamics in the O-CN land surface model: 2. Role of the nitrogen cycle in the historical terrestrial carbon balance. *Global Biogeochemical Cycles,* 24.

ZHANG, K., KIMBALL, J. S., MU, Q., JONES, L. A., GOETZ, S. J. & RUNNING, S. W. 2009. Satellite based analysis of northern ET trends and associated changes in the regional water balance from 1983 to 2005. *Journal of Hydrology,* 379**,** 92-110.

Aagaard Jakobsen, N., Zuchlinska Steen, M., Ahlström, M., Andersson, M., Langvall, O., 2022. The Asa High-yield Experimental Forest: A description of the infrastructure, available data and research potential. Sweden.

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