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# Under-sown ryegrass cover crops mitigate increased nitrogen leaching risks in a warming climate: Evidence from a 34-year field study in south-west Sweden

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ABSTRACT

The effects of repeatedly cultivating under-sown cover crops (CC) on nitrogen (N) leaching were investigated in a long-term field experiment in SW Sweden (1989–2023). Treatments with and without CC and with and without N fertilization were compared (CC_90N, 90N, CC_0N, and 0N). The impact of temperature, precipitation and the large-scale North Atlantic Oscillation index (NAOi) was also explored. N leaching was measured in separately tile-drained field plots in which also the yield of the main crop, biomass and N content of the cover crop, and soil nitrate were determined. The mean annual N concentration in drainage and the annual N leaching were significantly smaller in CC_90N than in 90N in 18 out of 34 years. A trend analysis showed that N concentrations in drainage increased significantly after 2010 in both treatments without CCs but not in those with CCs. The reduction in N leaching by growing CCs averaged 48 % (CC_90N) over the period and did not decrease over time. NAOi correlated with temperature and precipitation and showed a positive trend after 2010. NAOi was positively correlated with N leaching in 90N but not in CC_90N. Furthermore, NAOi was positively correlated with N content in CC biomass. Our results suggest that on-going climate change in Scandinavia and periods of high NAOi result in higher N mineralization and higher N leaching. The study also shows that under these circumstances, growing an under-sown ryegrass cover crop is an effective measure for environmental protection since its N uptake compensates for higher N mineralization.

## 1. Introduction

Marine and freshwater eutrophication is widespread in Europe (Sutton et al., 2011) and the agricultural sector is a major contributor (Leip et al., 2015). For example, in Sweden, agricultural activities contribute 39 % of the total anthropogenic nitrogen (N) load to coastal waters (Hansson et al., 2019). In this respect, coarse-textured soils located in the relatively wet climate of south Sweden are a significant source of N losses from agro-ecosystems (Stenberg et al., 1999). Jarvis et al. (2011) suggested that there are three categories of mitigation strategies that can be undertaken to reduce N pollution from agro-ecosystems, that is, to increase crop N uptake, reduce the N inputs, or prevent excess soil N from being lost. The third strategy can be implemented through the use of cover crops (CCs) growing between the main crops. CCs can be seeded together with the main crop (under-sown), often a cereal crop, or after harvest of the main crop. With a CC, a field that would otherwise have been tilled in autumn or left with stubble is covered with a crop. CCs take up N from the soil during autumn and incorporate it into their biomass. Thereby, soil mineral N from residual fertilizers or released by mineralization during autumn, which otherwise would have been exposed to leaching, is retained. Cover crops have been widely implemented in programs for reduced N leaching from arable land in Sweden and Denmark (Aronsson et al., 2016; Grant et al., 2006). The time between harvest and the first frost is relatively short in the Nordic countries, which limits the possible selection of CC species. Winter-hardy CCs may be advantageous since they are less subject to mineralization due to frost (Böldt et al., 2021), which can lead to N losses through leaching or $N_2O$ emissions (Andersen et al., 2025; Nasser et al., 2024). In a Danish study, frost-killed oilseed radish led to higher soil nitrate-N and $N_2O$ emissions compared to perennial ryegrass (Li et al., 2015). A compilation of studies from Scandinavia and Finland concluded that under-sown grass cover crops in cereals reduced N leaching by up to 89 %, and on average by 48 % (Aronsson et al., 2016). Several factors determine the uptake of N by the cover crop and the

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reduction of N leaching and also how much of the N that is taken up becomes available for the following main crop (residual effect) or is lost by leaching (Kumar et al., 2025). The time of incorporation of the CC into the soil has been found to be important for the residual effect (Alonso-Ayuso et al., 2014). In Denmark, it is recommended to incorporate CCs into the soil in spring (Thorup-Kristensen and Dresbøll, 2010) to maximize the CC growth period, minimize N leaching and to provide N for the next crop. In practice, CCs are often terminated and incorporated in late autumn, which may result in a smaller reduction of N leaching compared with spring incorporation of CCs (Norberg and Aronsson, 2024).

CCs can contain 12–66 kg N ha$^{-1}$ in the above-ground biomass (Kumar et al., 2025; Norberg and Aronsson, 2020; Thomsen and Hansen, 2014). Growing CCs repeatedly for long periods can therefore result in a build-up of soil organic nitrogen (SON), which increases the amount of N that is mineralized (Lewan, 1994; Thomsen and Christensen, 1999; Thorup-Kristensen et al., 2003). This may to some degree offset the beneficial effect of CCs in reducing N leaching, if the growing crops do not use this mineral N efficiently. In a long-term experiment (28 years), Norberg and Aronsson (2024) found that the difference in N leaching between treatments with and without CCs slowly decreased over time. However, these authors were not able to conclude that a build-up of SON was responsible for this phenomenon or whether it was due to other factors such as changes in the climate.

Agro-ecosystems in the North Atlantic region are influenced by both climate change as well as year-to-year variability governed by large-scale patterns such as the North Atlantic oscillation (NAO) (Mellander et al., 2018). Both temperature and precipitation during winter (November-April) were found to be significantly positively correlated with the NAO index (NAOi) in a Swedish study (Ulén et al., 2019). Chen and Hellström (2002) found that NAO influences temperature on both monthly and inter-annual scales, and to a lesser extent in summer compared with winter. Accounting for the regional and local effects of global warming and variations in large-scale weather patterns is important as they are likely to influence the effectiveness of different strategies to reduce N leaching (Mellander et al., 2018). Higher temperatures could increase N-mineralization and yields and also the growth and N uptake of CCs. Wetter and milder winters would increase drainage and thus the risk of N leaching (Øygarden et al., 2014).

The aim of this paper is to explore both the short- and long-term impacts of under-sown cover crops on subsurface drainage, N leaching, mineral N content in the soil profile, crop yields, CC biomass and N content. Long-term field experiments are very useful in this context, as they capture the effects of both short-term variations in weather and long-term trends in climate on N flows. The long-term field experiment (34 years) in south-west Sweden used for this study, had separately tile-drained plots with and without cover crops under contrasting N-fertilization. More specifically, we explore the following questions:

1. How does the growth, nitrogen uptake and efficiency of an under-sown cover crop vary among years?
2. Does the efficiency of the cover crop (in reducing nitrogen leaching) change in the long-term by growing and incorporating CCs into the soil, every year for more than 30 years?
3. How does the current climate change and the variability of the North Atlantic Oscillation (NAO) affect the N leaching and the efficiency of nitrogen uptake and retention by CCs?

## 2. Materials and methods

### 2.1. Experimental set-up, field site and management

The Mellby field trial (R0–8403) is an on-going long-term field experiment in the south-west of Sweden (lat. 56° 29’ N, long. 13° 00’ E, alt. 10 m). The climate of the region is cold temperate and semi-humid with a mean annual temperature at the field site of 8.2°C and an average annual precipitation of 812 mm (1984–2020 SMHIGridClim (Andersson et al., 2021)). It is a part of the Swedish University of Agricultural Sciences program for long-term field experiments (Bergkvist and Öborn, 2011). The field experiment consists of separately tile-drained plots (40 ×40 m), where the tile spacing is 9 m and the depth is 0.9 m (see Figure S1). The field area is flat with little spatial variation in soil properties. The topsoil is a sandy loam with a clay content of 5–10 %, a total carbon (C) content of 2.9 % and a total N content of 0.15 %. The sand deposits (90–130 cm) are underlain by a nearly impermeable glacio-fluvial clay (Johnsson, 1991). The main purpose of the field experiment is to compare N leaching under different cover crops, fertilizer management, and tillage practices in a spring cereal-dominated crop rotation (Table S1) (mainly oats (*Avena sativa)*, barley (*Hordeum vulgare)* and wheat (*Triticum aestivum*)). Since 2006, the rotation has been oats, barley and wheat. For this study, we selected treatments with and without an under-sown cover crop for further analysis and comparison, with measurements covering a 34-year period from 1989 to 2023. The CC was mostly perennial ryegrass (*Lolium perenne* L.), although red fescue was also used on two plots in 2006–2009, while in one year (1991), no cover crop was sown (Table 1). Winter rye (*Secale cereale*) was grown after potatoes in 1992 and 2002. Furthermore, the timing of tillage in the different CC plots was not completely consistent over time (Table 1). However, although only two of the three plots are strictly speaking replicates, we considered the treatments with and without CCs with application of mineral N fertilizer (CC_90N and 90N) to consist of three replicate plots (see Table 1). Both 90N and CC_90N received 90 kg N when barley, oats or triticale was grown, and 110 kg N ha$^{-1}$ yr$^{-1}$ when wheat, potato or rapeseed was grown. All crops received 20 kg P, and 64 kg K ha$^{-1}$ yr$^{-1}$. In addition, we present results from two single plots without N applications, hereafter referred to as unfertilized, with and without cover crops (CC_0N and 0N; Table 1, Figure S1). Data from these plots, which had the same main crop and cover crop as the fertilized treatments, are included here as references to show the temporal trends of contents of soil nitrate, total N concentration in drainage and total N leaching observed without N fertilization.

### 2.2. Water sampling and analysis

Subsurface drainage water from each plot was conducted to an underground monitoring station. Tipping bucket flow gauges were used to measure the flow rate. Grab samples were taken every two weeks from 1989 to 1998. Thereafter, flow-proportional water sampling was carried out, such that sub-samples of 15 ml were taken for every 0.2 mm of drainage water. The subsamples were pumped into bottles, which were sent for laboratory analysis every two weeks during periods with drainage. Total N was determined on unfiltered water samples according to European standards (SIS 028131 until 2009, EN 12260–1 during 2010–2014 and SS-EN 12260–2 from 2014). For the period with grab sampling, daily total N concentrations were obtained by linear interpolation between sampling events. For the period with flow-proportional water sampling, the measured concentration for each sampling period of two weeks was used for each day during the period. The daily N leaching was calculated by multiplying the daily discharge from each plot with the daily N concentration. These daily values were summed to annual values for the agro-hydrological year (1st July to 30th June). Mean annual concentrations of total N were calculated by dividing the annual load of total N by the annual drainage.

### 2.3. Cover crop biomass and yields of the main crops

The above-ground biomass of the cover crop (including weeds) was sampled by taking cuttings from three separate small sub-plots (0.25 m$^2$) in each plot (Oct-Dec). Samples were weighed and dried at 60°C before determination of dry matter and total N. Grain yield of the main crop was measured by harvesting three sub-plots (20 m$^2$) in each plot. Concentrations of N in CC biomass were determined by dry combustion (ISO

**Table 1**

Experimental set-up in the eight plots for the four treatments (90N = 90 kg nitrogen (N) fertilizer ha$^{-1}$ yr $^{-1}$, CC = cover crop, 0N = no fertilization) during the period 1989–2023. Cover crop (CC) treatments were consistent with one exception during 1991 and the species used in two plots in 2006–2009. Tillage treatments differed between different periods in plots 11–14. The time of tillage refers to the first tillage event after harvest of the main crop, which was stubble cultivation in plots without CCs (plot 2, 7, 11 and 12) and mouldboard ploughing in CC plots (plot 5, 10, 13 and 14).

| | Treatment | 90N | 90N | CC_90N | CC_90N | CC_0N | 0N |
|---|---|---|---|---|---|---|---|
| Year | Plot no | 2 | 11,12 | 10 | 13,14 | 5 | 7 |
| 1989–1990 | Cover crop | | | Italian ryegrass | Italian ryegrass | Italian ryegrass | |
| | Tillage | September | September | March-April | March-April | March-April | September |
| 1991 | Cover crop | | | Perennial ryegrass | No CC | Perennial ryegrass | |
| | Tillage | September | October | March-April | October | March-April | September |
| 1992–1998 | Cover crop | | | Perennial ryegrass* | Perennial ryegrass | Perennial ryegrass* | |
| | Tillage | September | March-April | March-April | March-April | March-April | September |
| 1999–2005 | Cover crop | | | Perennial ryegrass* | Perennial ryegrass* | Perennial ryegrass* | |
| | Tillage | September | November-December | March-April | November-December | March-April | September |
| 2006–2009 | Cover crop | | | Perennial ryegrass | Red fescue | Perennial ryegrass | |
| | Tillage | September | March-April | March-April | March-April | March-April | September |
| 2010–2023 | Cover crop | | | Perennial ryegrass | Perennial ryegrass | Perennial ryegrass | |
| | Tillage | September | September | March-April | March-April | March-April | September |

*Winter rye (Secale cereale) was grown instead of ryegrass after potatoes in 1992 and 2002.

10694, 1995 and ISO 13878, 1998) using an elemental analyzer (TruMac CN analyzer).

### 2.4. *Soil samples and analysis*

Soil samples were taken in spring before fertilization (February-May) then directly after harvest of the main crop (July-September) and finally in late autumn before ploughing (October-December). Samples were taken at 0–30, 30–60, and 60–90 cm depth and kept frozen (-18 °C) until analysis. Nitrate-N ($NO_3$-N) was analyzed colorimetrically after extraction with 2 M KCl.

### 2.5. *Climate data*

Daily air temperature and precipitation were retrieved from a gridded database, SMHIGridClim (Andersson et al., 2021), provided by the Swedish Meteorological and Hydrological Institute (SMHI), with a horizontal resolution of 2.5 km for the period 1989–2018. For the remaining years, another gridded database, PTHBV was used, which has a horizontal resolution of 4 km (Johansson and Chen, 2003). Monthly values of the North Atlantic Ocillation index (NAOi) were retrieved from the NOAA Climate Prediction Centre (www.noaa.gov) (Figure S2). All climate variables were grouped by agro-hydrological years and summarized by calculating the mean (air temperature and $NAO_i$) or the sum (precipitation).

### 2.6. *Statistics*

Mann-Kendall and Sen's slope estimator tests were used to test for monotonic trends in temperature and precipitation and their magnitude. The correlation between NAOi and climate variables (air temperature and precipitation) was investigated by linear regression. Student's *t*-test was used to compare CC_90N with 90N for significant differences between treatments on a yearly basis. This test was not performed for the unfertilized treatments since they were not replicated. A generalized additive model (GAM) was used to test for any significant trends in mean annual N concentration. This was done with the visualization toolbox developed by Von Brömssen et al., (2021). Briefly, a thin plate spline was utilized to model the trend curve. The first derivatives of the smoothed trend were calculated using finite differencing and the corresponding 95 % confidence intervals were determined. If the confidence band did not include zero, the trend was considered significant at that point in time. The benefit of this type of model is that it can be used to reveal directional changes in time series data. Spearman correlation analysis was performed for different N variables and weather variables across all agrohydrological years. All statistical analyses were performed in R (Core Team, 2024). $P < 0.05$ was used as the significance level.

## 3. Results

### 3.1. *Climate and hydrology*

The mean annual temperature for the period 1989–2023 was 8.5 °C. According to the Mann-Kendall test, there was a significant increase in temperature during this period ($p = 0.001$) and Sen's slope indicated a yearly increase of 0.05°C. The mean annual precipitation was 797 mm (Fig. 1A) and no monotonic trend was detected. Generally, drainage occurred from August until April (Fig. 1B). Annual drainage (calculated from 1st July to 30th June) was on average 281 mm, ranging from 41 mm in 2020/2021 to 499 mm in 1998/1999. No monotonic trend in drainage was detected. The mean annual drainage from plots with and without CCs did not differ significantly in any of the years. NAOi based on agrohydrological years was significantly correlated with both temperature and precipitation during winter months (October-March) (R=0.44 and 0.38, respectively (Figure S3)). The correlation was somewhat stronger if using NAOi mean values based on only winter months (R=0.6 and 0.44 for temperature and precipitation (Figure S4)).

### 3.2. *N concentration in drainage water and N leaching*

Mean annual N concentration in the drainage water was significantly smaller in the CC_90N treatment than in the 90N treatment in 18 out of 34 years (Fig. 2) and varied between 1.85-16.7 and 4.2-35.9 mg N L$^{-1}$ year$^{-1}$ for CC_90N and 90N respectively. No monotonic trends in N concentration during the experiment were detected by Mann-Kendall tests for any of the treatments. However, the GAM analysis indicated an increase in mean annual concentration for both treatments without cover crops (90N and 0N), starting from around 2010 (Fig. 3). There was no such trend in the treatments with cover crops.

Mean annual N leaching in the treatment without CC (90N) was significantly larger than that of the cover crop treatment (CC_90N) in 17 out of 34 years (Fig. 4). The reduction in N leaching achieved by growing CCs was on average 48 % over the whole period, with annual values ranging from an increase of 10 % in 2002/2003 following a potato crop to a reduction of 82 % in 1989/1990 (Fig. 5). In 2008/2009, 2013/2014, and 2019/2020, the CC was terminated early (in September) as the whole field was treated with glyphosate after harvest to get rid of perennial weeds. Annual mean total N leaching for the whole experimental period was 18.6 ± 1.4 and 33.9 ± 1.6 kg N ha$^{-1}$ for CC_90N and 90N and 10.2 ± 1.8 and 16.7 ± 1.7 kg N ha$^{-1}$ for CC_0N and 0N. The summer in 2018 was exceptionally dry (only 9.5 mm of rainfall in May, 25.7 mm in June, and 6.8 mm in July). As a result, crop growth, uptake

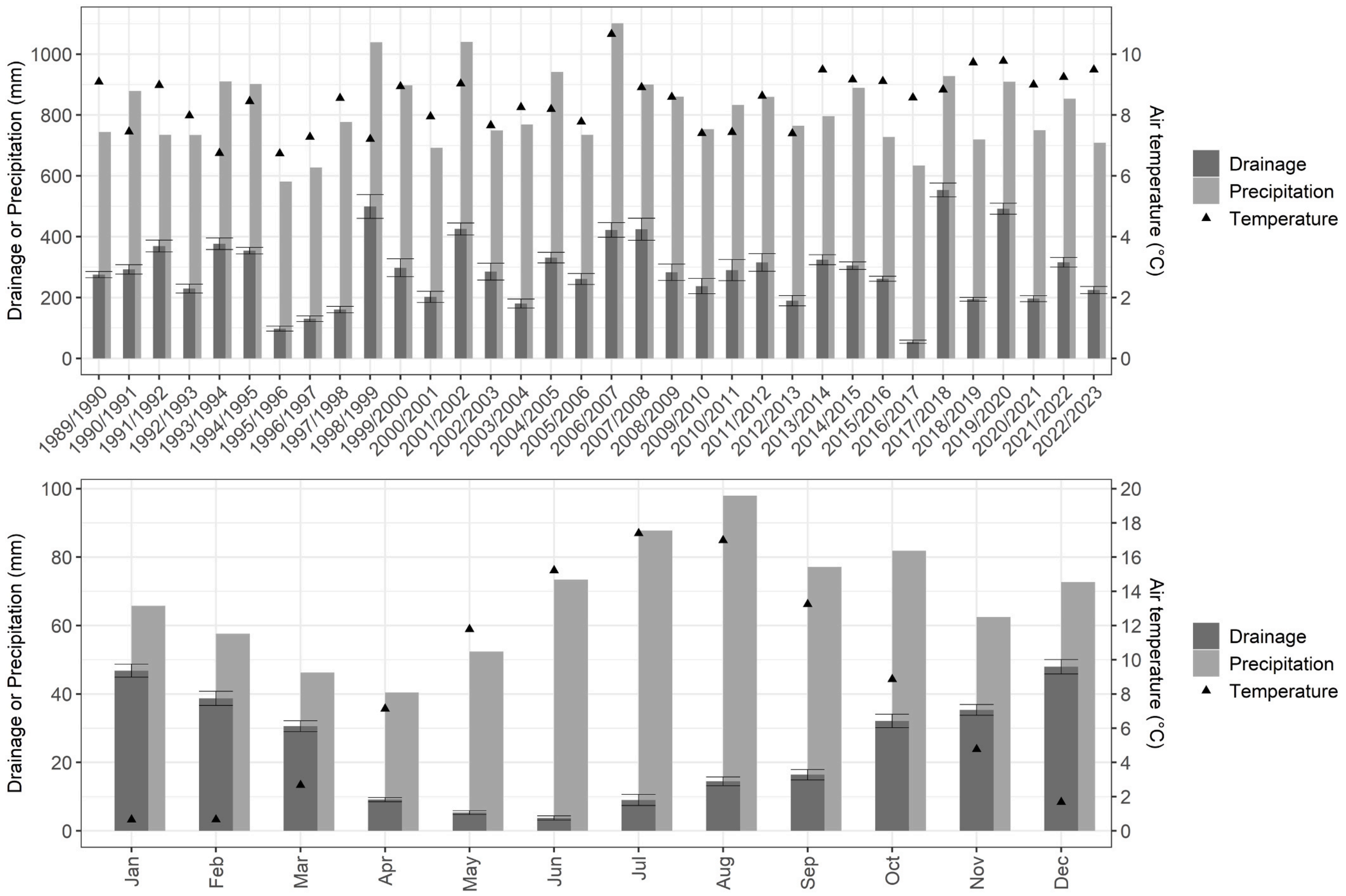

**Fig. 1.** Mean annual (A) and monthly (B) precipitation (mm), air temperature (°C) and discharge (mm) for the 8 plots over the years 1989–2023. Bars show standard error for the 8 plots.

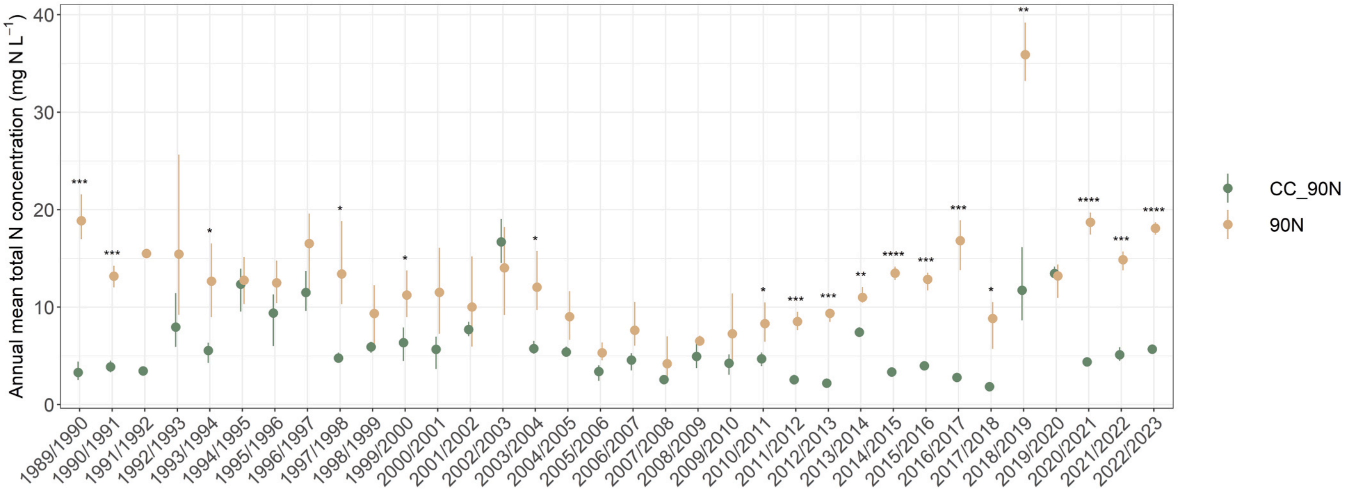

**Fig. 2.** Annual mean concentration (mg L$^{-1}$) of total nitrogen (N) for treatments with fertilization and with and without cover crops (CC_90N and 90N, n = 3). Stars represent significant differences between treatments (*=$p < 0.05$, **=$p < 0.01$, ***=$p < 0.001$, ****=$p < 0.0001$).

of N by the main crop and yields were drastically reduced, which led to very high N-concentrations (Fig. 2) and leaching losses of N (Fig. 4) in 2018/2019 in the 90N treatment. However, N concentrations and N leaching losses in this year were significantly smaller in the CC_90N treatment (24.3 kg N ha$^{-1}$ compared to 70.3 kg N ha$^{-1}$ in the 90N treatment). In the following year (2019/2020), when all plots were treated with glyphosate in September, N concentrations and N leaching losses were high and of similar magnitude in both treatments.

### 3.3. Soil $NO_3$-N

Differences in $NO_3$-N contents in soil between treatments with and without CCs were largest in late autumn (Fig. 6). This was mainly due to larger amounts of $NO_3$-N in the subsoil in the treatments without CCs,

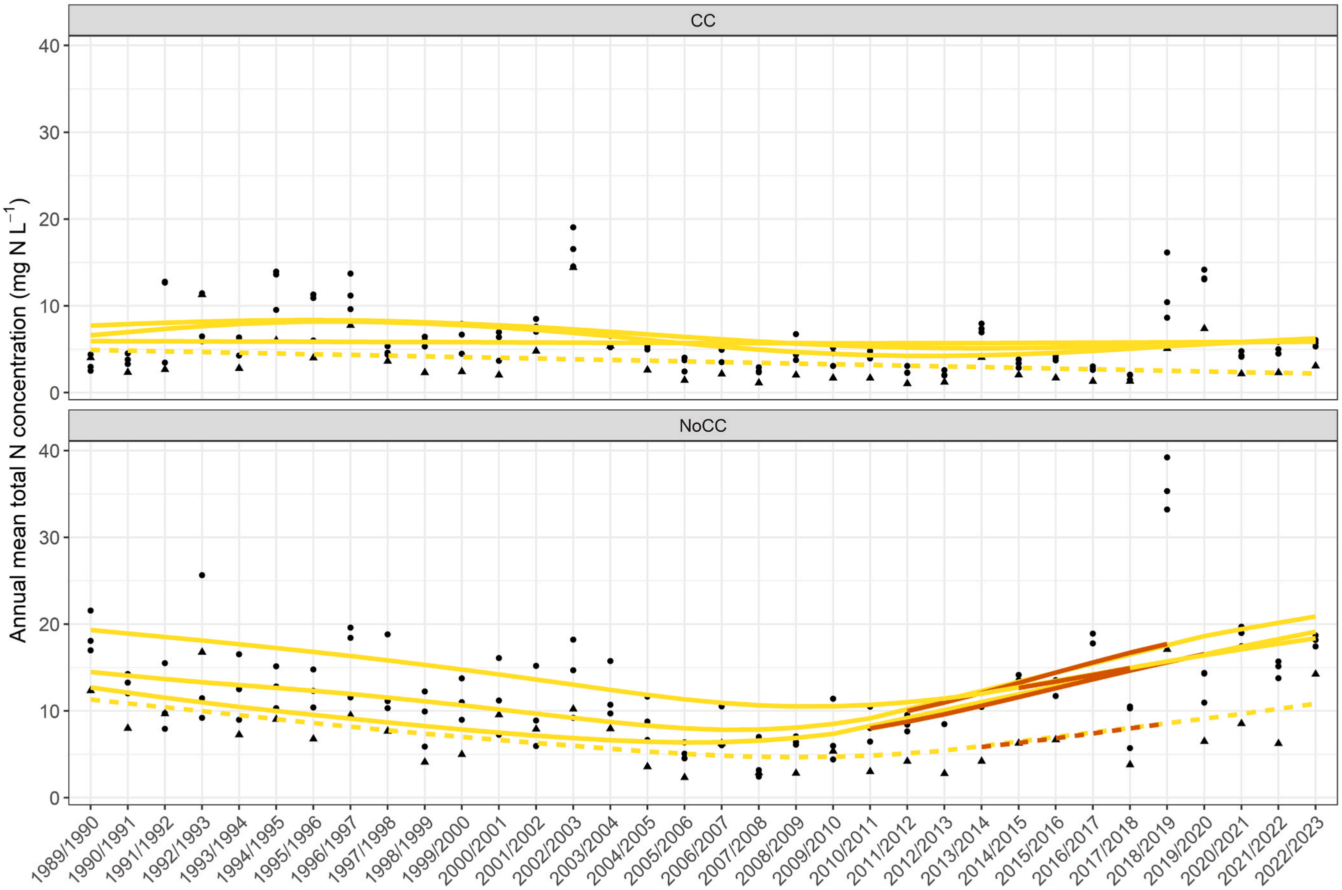

**Fig. 3.** Generalized additive model (GAM) fit to total nitrogen (N) concentration (mg L$^{-1}$) in drainage water for field plots with cover crop (CC, top panel) and without cover crop (NoCC, bottom panel), one line per replicate. The dashed lines and triangles represent the unfertilized treatments. Red color indicates a significant increasing trend.

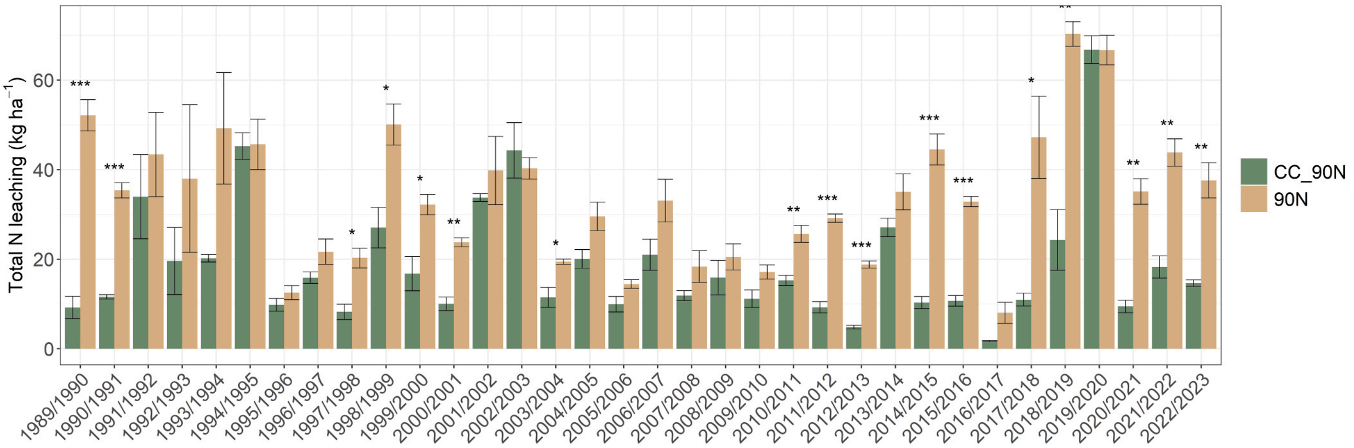

**Fig. 4.** Mean annual total nitrogen (N) leaching (kg ha$^{-1}$) for treatments with and without an under-sown cover crop (CC_90N and 90N, n = 3). Stars represent significant differences between treatments (*=$p < 0.05$, **=$p < 0.01$, ***=$p < 0.001$).

which indicates a downward movement of leachable N in these treatments (Fig. 6). This also appeared true for the plot without CCs, which received no mineral N fertilizer (0N), where the $NO_3$-N content was larger compared to CC_90N both in late autumn and in spring. $NO_3$-N contents were significantly larger in the 90N treatment compared with CC_90N regardless of sampling time. On average, they were 1.6 times larger in spring (37.1 vs 23.6 N kg ha$^{-1}$), 1.5 times larger at harvest (20.7 vs 13.6 N kg ha$^{-1}$), and 2 times larger in late autumn (25.6 vs 12.7 N kg ha$^{-1}$).

### 3.4. *Yield of the main crop and biomass of the cover crop*

The yields of the main crop were not significantly affected by an under-sown cover crop (Fig. 7). Fig. 7 also shows that yields (oat) were at their lowest in 2018 due to the severe summer drought (503 ± 67.5 and 428 ± 62.9 kg ha$^{-1}$ for CC_90N and 90N respectively). In the

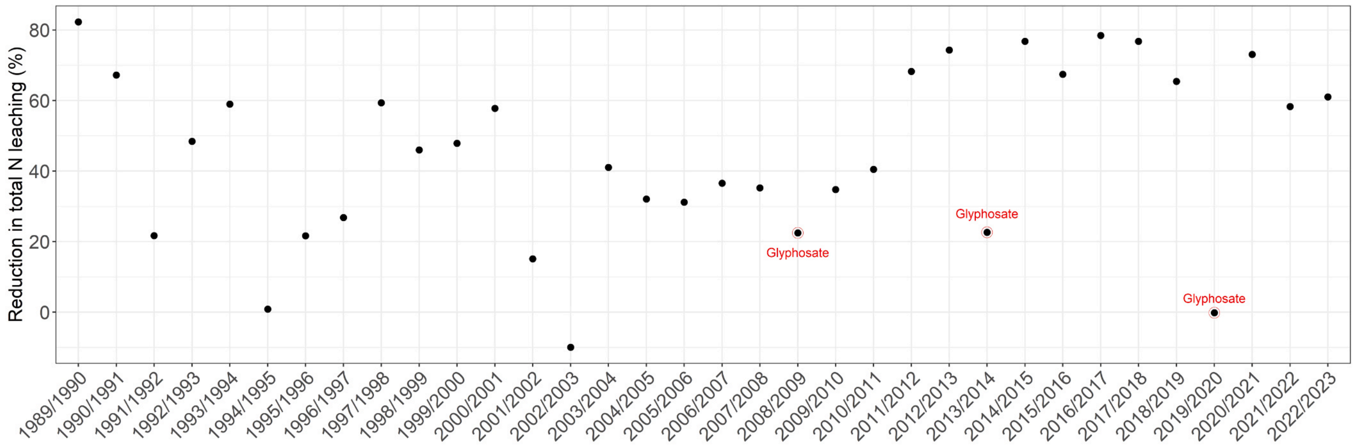

**Fig. 5.** Reduction in annual nitrogen (N) leaching in the treatment with cover crop (CC_90N) compared to that without a cover crop (90N).

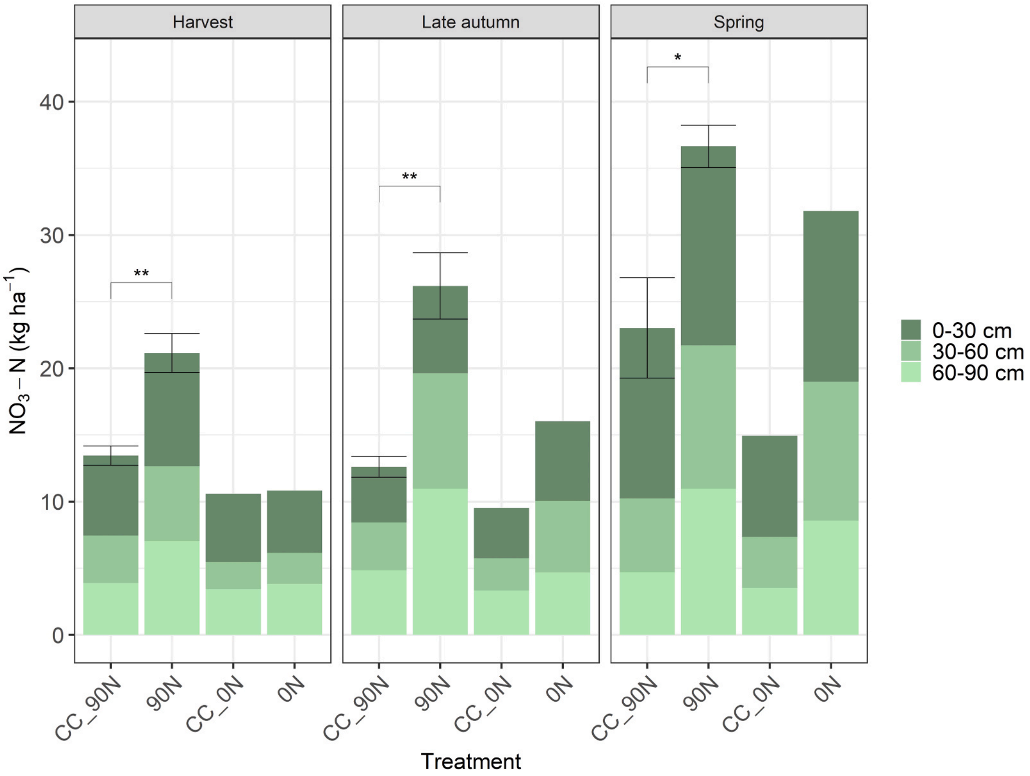

**Fig. 6.** Mean soil nitrate nitrogen ($NO_3$-N, kg ha$^{-1}$) in treatments with and without an under-sown cover crop and fertilization (n = 3 for CC_90N and 90N, n = 1 for CC_0N and 0N). Samples were taken at three sampling periods (at harvest, in late autumn and spring) over 34 years, at three soil depths (0–30, 30–60 and 60–90 cm). Error bars represent standard error for the whole profile. Stars represent significant differences between fertilized treatments for the whole profile (*=$p < 0.05$, **=$p < 0.01$).

unfertilized plots, yields in 2018 were 450 kg ha$^{-1}$ for CC_0N and 415 kg ha$^{-1}$ for 0N.

The above-ground biomass of cover crops and weeds at the time of incorporation was on average 980 ± 94.8 kg ha$^{-1}$ (min 26.1 – max 1870 kg ha$^{-1}$) for CC_90N (Fig. 8A). The amount of N in the cover crops was on average, 17.8 ± 1.59 kg N ha$^{-1}$ and ranged between 1.1 and 48.5 kg N ha$^{-1}$ on an annual basis (Fig. 8B). No significant trend was detected. In the unfertilized plot (CC_0N), CC biomass was on average 828 kg ha$^{-1}$, ranging between 30.7 and 1973 kg ha$^{-1}$ while N uptake was on average 15.1 and ranged from 1.24 to 29.2 kg N ha$^{-1}$.

### *3.5. Relationships between N variables and climate*

The Spearman rank correlation coefficients revealed a positive correlation between annual mean temperature and N leaching in 90N ($\rho$=0.4, $P < 0.05$) but not in CC_90N (Fig. 9). Precipitation was negatively correlated with the N concentration in drainage water in 90N ($\rho$=-0.48, $P < 0.05$) and positively correlated with N leaching in both 90N ($\rho$=0.35, $P < 0.05$) and CC_90N ($\rho$=0.42, $P < 0.05$). Positive correlations were found between annual mean $NAO_i$ and soil $NO_3$-N content in late autumn ($\rho$=0.44, $P < 0.05$) and annual N leaching ($\rho$=0.64, $P < 0.05$) in the 90N treatment, but not in CC_90N. $NAO_i$ was positively correlated to the N content in CC biomass ($\rho$=0.48, $P < 0.05$) and negatively correlated to spring soil $NO_3$-N content ($\rho$=-0.38, $P < 0.05$)

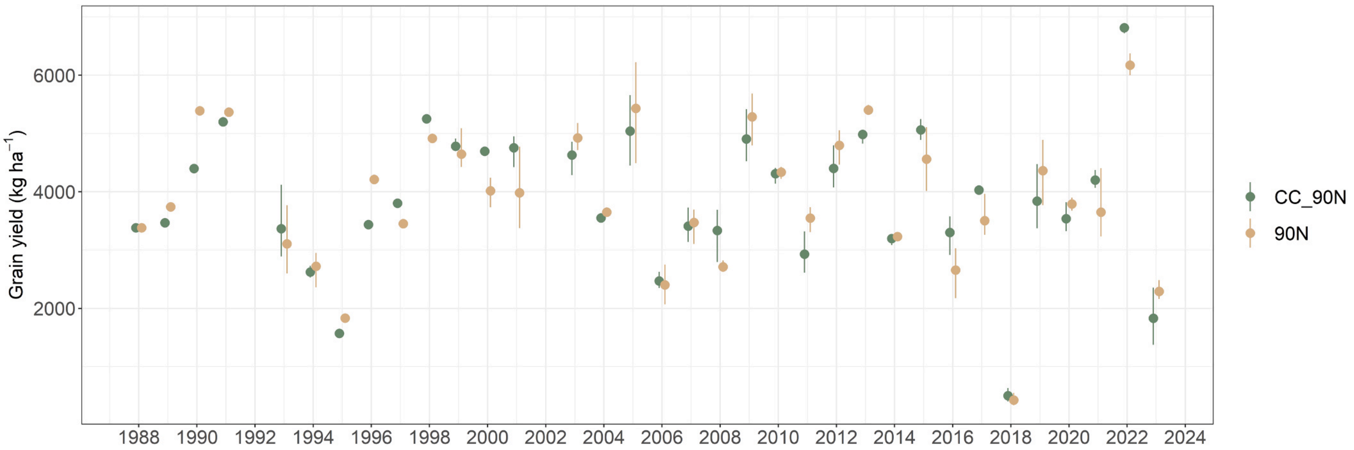

**Fig. 7.** Grain yield (kg ha$^{-1}$) for cereal crops in treatments with (CC_90N) and without (90N) cover crop. Years with potatoes were excluded. Dots represent the mean and the lines indicate min/max values of the three replicates.

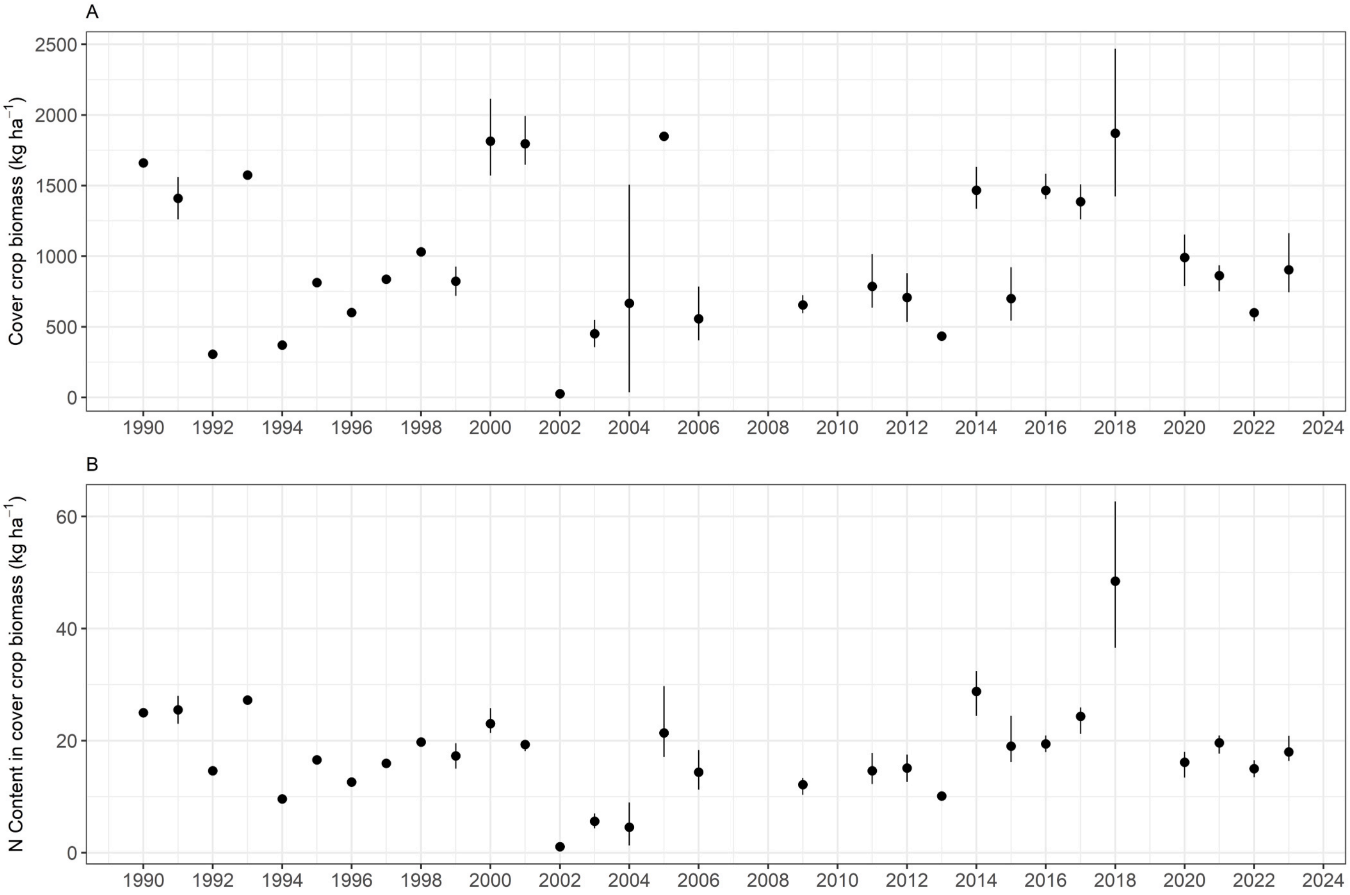

**Fig. 8.** Cover crop biomass (kg dry matter ha$^{-1}$) above ground (A), and N content in biomass (kg ha$^{-1}$) (B) at the time of incorporation. Dots represent the mean and the lines indicate min/max values of the three replicates.

in the CC_90N treatment (Fig. 9). Drainage was uncorrelated to NAOi in both treatments (not shown). We also tested the correlation between NAOi based on winter months (October-March) and N variables. For these tests, NAOi was only significantly correlated with N leaching in 90N ($\rho$=0.53, $P < 0.05$) and N content in CC biomass in CC_90N ($\rho$=0.37, $P < 0.05$).

## 4. Discussion

### 4.1. *Climate and hydrology*

The Mann-Kendall test showed a significant (positive) trend for temperature but no trends were detected for drainage or precipitation. There was also no significant difference in drainage between treatments with and without CCs. Norberg and Aronsson (2020) also found no difference in drainage between plots with and without CCs in a similar

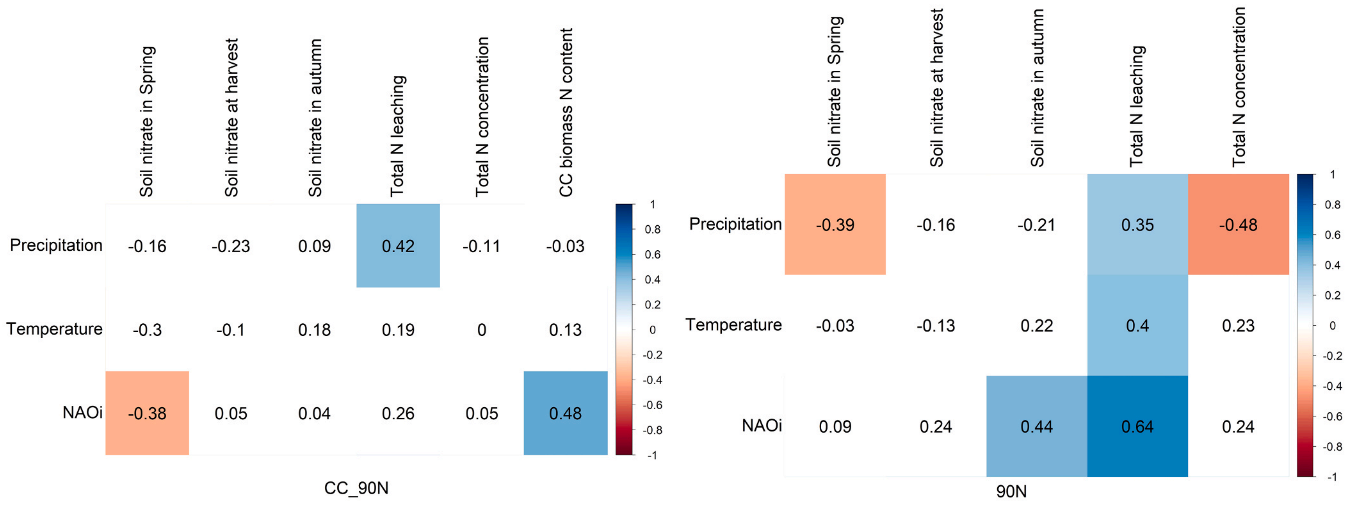

**Fig. 9.** Spearman rank correlation coefficients (ρ) for relationships between nitrogen (N) variables and weather variables for the treatments with and without cover crop, CC_90N (left) and 90N (right). Significant correlations ($P < 0.05$, $n = 34$) are highlighted in red (negative) or in blue (positive). All variables except soil nitrate and CC biomass N content were summarized for agrohydrological years (1st July- 30th June).

tile-drained field experiment, located about 100 km south from the site in this study. These results are in contrast to the vast majority (90 %) of studies included in a recent review paper by Meyer et al. (2019), who looked at reductions in drainage from cultivation of CCs in temperate climates. They found a mean weighted reduction of between 27 and 37 mm per year compared to winter bare soil. The climate in Sweden, with cold humid winters during which solar radiation is limiting for evapotranspiration processes might result in negligible differences between soils with and without a cover crop. It might also be the case that the variability among individual plots is masking any potential differences between the treatments.

### 4.2. Mean annual N concentration in drainage and N leaching in relation to climate

The increase in N concentrations in drainage water in both treatments without CCs, which started shortly after 2010, suggests that a change in the climate may have affected N leaching on plots without CCs (Fig. 3). Kyllmar et al. (2023) used GAM analysis on agricultural catchments in the Nordic-Baltic region and found a significant increase starting soon after 2010 in annual mean total N concentrations in seven out of eight catchments in Sweden. This could be due to higher temperatures inducing increased mineralization of organic nitrogen (Thomsen et al., 2010). In our study, annual mean temperature did not correlate significantly with total N concentration in any of the treatments (Fig. 9). On the other hand, N leaching was positively correlated with annual mean temperature in the 90N treatment (Fig. 9).

The high N-concentrations in drainage water and N leaching in 2018/2019 (Figs. 2 and 4) following a severe summer drought were due to a much smaller uptake of N by the main crop (Fig. 7), such that significant amounts of residual fertilizer N and mineralized N (Manzoni et al., 2012) remained in the soil after harvest, which was prone to leaching in the autumn and winter. These excessive amounts of N left in the soil, were lost by leaching in the 90N but were efficiently taken up by the cover crop in the CC_90N. Similar findings were reported for the drought year of 2018 by Kumar et al. (2025) in a Danish field experiment and by Klages et al. (2020) in a German case study.

### 4.3. Long-term efficiency of the cover crop

The results of this study represent a sandy soil in a cold temperate humid climate, where N uptake by vegetation during autumn is especially important to reduce N leaching. The effects of cover crops may be smaller and more variable for soils less prone to leaching, as found by Norberg and Aronsson (2020) for a clay soil in southern Sweden. Nevertheless, the mean reduction in N leaching due to cover crops at Mellby corresponds well to a meta-analysis of studies in the Nordic countries in which the reduction by under-sown grasses was also on average 48 % (Aronsson et al., 2016).

The difference in N leaching between CC_90N and 90N at Mellby did not decrease with time (Fig. 5). This is in contrast with data from a similar field experiment (Fotegården) situated about 250 km further north in Sweden, where Norberg and Aronsson (2024) found a significant reduction in the efficiency of the CCs (mostly ryegrass) during 28 years. Furthermore, the difference in N concentrations in drainage water between treatments with and without CC was not significant in most years at Fotegården. This may be due to a lower mineralization of organic N compared to Mellby, where N mineralization was found to be high enough to sustain yields for 35 years in a plot without any N fertilizer (Nimblad Svensson et al., 2025). Differences in climate may also play a role: the Mellby site receives, on average, 134 mm more precipitation per year and the mean annual temperature is 0.8 °C higher. Another reason for the difference in cover crop efficiency for N uptake between sites may be that both treatments compared in Fotegården were tilled in spring whereas the 90N-treatment at Mellby was tilled in autumn. Finally, it should also be noted that although not shown here, no trend was apparent that would suggest an increase with time in SON content and thus N mineralization in the treatment with cover crops at Mellby. The application of a process-oriented soil-vegetation model could lead to a better understanding of the long-term impacts of repeated incorporation of cover crop biomass and the potential changes of SON, N mineralization and N leaching in a warming climate, both at Mellby and at other sites.

$N_2O$ emissions also have a negative impact on the environment (Andersen et al., 2025; Nasser et al., 2024) and might also be affected by the presence of cover crops. Such measurements were not made in this experiment, but we assume that little N is lost as $N_2O$ from winter hardy CCs incorporated in spring (Li et al., 2015), especially for a sandy soil like Mellby.

### 4.4. Soil $NO_3$-N

Soil $NO_3$-N contents at the time of harvest were significantly lower in CC_90N compared to 90N (Fig. 6), which indicates that the CCs reduce the amount of $NO_3$-N already during the growing season. During late autumn, a significant amount of $NO_3$-N had been mineralized, and much of it was leached downwards in the profile and lost through the tile-drainage in 90N. In contrast, in CC_90N, the amounts of $NO_3$-N at the time of harvest and in late autumn were of similar magnitude (Fig. 6). In spring, $NO_3$-N increased in both treatment, especially in the topsoil, where the amounts were very similar between the treatments. For cover crops incorporated in spring, N uptake over winter may result in lower availability of soil N for the next crop through pre-emptive competition (Thorup-Kristensen and Dresbøll, 2010). This seemed not to be the case here and supports the results from Thorup-Kristensen and Dresbøll that cover crops should preferably be kept over winter on sandy soils in wet climates. The low N uptake of the CCs in spring could be due to the soil temperature being too low for any significant crop growth but still high enough for mineralization to occur (Van Schöll et al., 1997). For the single plots without N fertilizer application, it was not possible to evaluate differences with statistical methods. However, a considerable accumulation of leachable N in the spring was observed and the use of CCs led to a reduction of a similar magnitude as in the fertilized plots. This confirms that the soil at Mellby has a capacity for sustaining N mineralization for a long time, as was also shown by Nimblad Svensson et al. (2025).

### *4.5. Crop yield and cover crop biomass*

In this experiment with cover crops under-sown in the main crop almost every year, the yield of the main crop can be affected both by the competition from the cover crop (potentially reducing yields) as well as by the residual effects of cover crop incorporation in spring (potentially increasing yields). A meta-analysis for Nordic countries found an average reduction in yields of the main crop of 3 % for non-legume under-sown CCs (Valkama et al., 2015). We did not find significant effects of under-sown CC's on main crop yields in our study, which suggests that the effect of competition and residual effects from CC incorporation cancelled each other, as was also indicated in the study by Kumar et al. (2025). Residual effects on crop yields of non-legume cover crops are often zero or sometimes even negative (Tonitto et al., 2006).

The average N content in the above-ground biomass of CCs was 18 kg N $ha^{-1,}$ which is close to the median for the range (7–38 kg N $ha^{-1}$) reported in a review of studies carried out in the Nordic countries (Aronsson et al., 2016). The above-ground N content of the CC in spring 2019 was 48.5 kg N $ha^{-1}$, presumably as a consequence of the large amount of residual N available to the CC following the summer drought of 2018. Thus, the potential N-uptake by under-sown perennial ryegrass is much higher than is observed in most years.

### *4.6. Influence of the NAO on N leaching and cover crop N uptake*

The long-term data series enabled us to see interactions between N leaching and oceanic-scale climate patterns (NAO), which seem to influence treatments with and without CCs differently. Periods with high $NAO_i$ (i.e. milder winters) were associated with higher N leaching in the 90N treatment, while the CC_90N treatment was not significantly affected. At the same time, the N-content in the above-ground biomass of the cover crop was positively correlated with NAOi. It therefore seems that increases in N mineralization likely to be associated with higher values of the NAOi were effectively buffered by a greater uptake of N by the cover crops, so that leaching did not increase in the CC_90N treatment. In a pot experiment carried out in Denmark under low light conditions in autumn, Thomsen et al. (2010) found that ryegrass efficiently extracted all the inorganic N from the soil at elevated temperatures of 4 and 8°C, even though 22 and 80 % more N was mineralized, respectively, compared to the control. Mellander et al. (2018) found positive correlations between $NO_3$-N concentrations in rivers and $NAO_i$ during 2010–2016 for two catchments in Ireland and one in Norway ($R^2 = 0.87$, 0.57 and 0.76 respectively).

## 5. Conclusions

Perennial ryegrass under-sown into spring cereals reduced N leaching, on average by 48 % over 34 years without affecting grain yields. The cover crop was also able to efficiently compensate for increased soil nitrate-N in the autumn, following a summer with a severe drought and low N uptake by the main crop. The efficiency of the CCs with respect to reducing N leaching did not decrease during the experimental period of more than three decades. The contribution of CCs to soil organic nitrogen, which may lead to increased mineralization, seems to be much lower than their potential and actual N-uptake. Process-based soil-vegetation models would be useful to further improve our understanding of the interactions between cover crop growth, frequent incorporation of cover-crop biomass and the long-term changes of soil N mineralization and N leaching in a warming climate with more extreme weather.

Annual mean temperature showed a significant positive trend over the period and total N leaching was positively correlated with temperature in the treatment without cover crops (90N) but not in the treatment with cover crops (CC_90N). The North Atlantic Oscillation varied over the period and was positively correlated with N leaching in 90N and with N uptake by CCs in CC_90N. In both fertilized and unfertilized treatments without CCs, N concentration in the drainage water increased through time, from around 2010 until 2019, which coincided with a period of high NAOi. No such trend in N concentrations in drainage was found in plots with under-sown CCs. These results strongly suggest that growing CCs might become even more important given ongoing climate change in Scandinavia, in order to adapt cereal cropping systems from an environmental perspective by reducing N leaching. By increasing N uptake, perennial ryegrass was able to compensate for increased risks of N losses during periods with increasing N mineralization in soil.

## CRediT authorship contribution statement

**Helena Aronsson:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Data curation. **David Nimblad Svensson:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Elisabet Lewan:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Lisbet Norberg:** Writing – review & editing, Investigation, Data curation.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.110090.

## Data availability

Data will be made available on request.

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