Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2026:13
Faculty of Natural Resources and Agricultural Sciences

Cover crop impacts on N cycling in a changing climate

Long-term modelling of spring cereal systems with and without cover crops in south-west Sweden

David Nimblad Svensson

Cover crop impacts on N cycling in a changing climate

Long-term modelling of spring cereal systems with and without cover crops in south-west Sweden

David Nimblad Svensson
Faculty of Natural Resources and Agricultural Sciences
Department of Soil and Environment
Uppsala

SWEDISH UNIVERSITY
OF AGRICULTURAL
SCIENCES

DOCTORAL THESIS
Uppsala 2026

Acta Universitatis Agriculturae Sueciae
2026:13

Cover: The field next to my house in July 2024 (Photo D. Nimblad Svensson)
ISSN 1652-6880
ISBN (print version) 978-91-8124-210-2
ISBN (electronic version) 978-91-8124-230-0
https://doi.org/10.54612/a.4qvuiq5pba

Swedish University of Agricultural Sciences, Department of Soil and Environment, Uppsala, Sweden

Print: SLU Grafisk service, Uppsala 2026

Cover crop impacts on N cycling in a changing climate: Long-term modelling of spring cereal systems with and without cover crops in south-west Sweden

Abstract

Climate change is expected to increase nitrate leaching from arable land in the Nordic countries due to increases in temperature and winter precipitation. Growing cover crops (CCs) is the most important mitigation strategy in spring cereal dominated systems. In this thesis, data from a long-term field experiment in south-west Sweden was used to study the effects of growing under-sown perennial ryegrass (*Lolium perenne* L.) as a cover crop on N leaching, soil organic nitrogen (SON), N mineralisation and yield under present and future climate. The methodology involved statistical analysis of 34 years of field measurements combined with simulation modelling. The model was calibrated against field data from treatments with (CC_90N) and without (90N) cover crops. It was also used to make projections for future climate (2020–2100) with input from five coupled global and regional climate models for three representative concentration pathways (RCP 2.6, 4.5 and 8.5). The CC effectively reduced N leaching with no decline in efficiency over 34 years. Total N leaching in 90N was positively correlated with temperature and the North Atlantic Oscillation index (NAOi), whereas in CC_90N, only N uptake by the CC was positively correlated with NAOi. Model simulations showed that annual N mineralisation in CC_90N increased over time due to higher temperatures and the repeated incorporation of CC biomass into the soil. Nevertheless, simulated N leaching increased more in 90N than in CC_90N. N uptake by the CC increased substantially in a future climate, partly because harvest of the main crop occurred earlier in the season, especially in scenarios with RCP 4.5 and 8.5. The cover crop efficiency expressed as % reduction in N leaching compared to the treatment without CC, increased over time under RCP 8.5. Thus, under-sown perennial ryegrass could efficiently compensate for both earlier harvests and increases in N mineralisation in a warming climate. Yields did not differ between the two treatments in the current climate, while simulated SON increased in CC_90N, but decreased over time in 90N both in present and future climates.

Keywords: Nitrogen leaching, cover crops, climate change, agroecosystem modelling, climate scenarios

Mellangrödors påverkan på kväveomsättningen i ett varmare klimat: Modellering av odlingssystem med och utan mellangrödor i sydvästra Sverige

Sammanfattning

Klimatförändringar förväntas öka läckaget av nitrat från jordbruksmarker i de nordiska länderna till följd av ökad temperatur och vinternederbörd. Den viktigaste åtgärden för att minska kväveläckaget efter vårspannmål är att odla mellangrödor när marken annars skulle ha varit utan växttäcke. I den här avhandlingen studeras effekterna av engelskt rajgräs (*Lolium perenne* L.) som insådd mellangröda på kväveläckage, organiskt markkväve, kvävemineralisering och skörd. Skillnader mellan led med och utan årlig insådd av mellangröda undersöktes under nutida och framtida klimat, baserat på statistisk analys av 34 års mätdata från ett fältexperiment i sydvästra Sverige och simuleringar med en processbaserad mark-växtmodell (CoupModel). Modellen kalibrerades mot mätdata från behandlingar med (CC_90N) och utan (90N) insådd mellangröda. Den användes även för att göra projektioner in i framtiden (2020–2100) med drivdata från fem kombinationer av globala och regionala klimatmodeller för tre utsläppsscenarier (RCP 2.6, 4.5 och 8.5). Mellangrödan reducerade observerat kväveläckage under 34 år, utan att effektiviteten avtog. Kväveläckaget i 90N-ledet var positivt korrelerat med temperatur och det nordatlantiska oscillationsindexet (NAOi) medan i CC_90N, var enbart mellangrödans kväveupptag positivt korrelerat med NAOi. Modellsimuleringarna visade att den årliga kvävemineraliseringen i CC_90N-ledet ökade över tid på grund av högre temperaturer och återkommande inkorporering av fånggrödans biomassa. Trots detta så ökade kväveläckaget mer i 90N-ledet. Mellangrödans kväveupptag ökade markant i framtida klimat, delvis på grund av att skörden av huvudgrödan inträffade tidigare, särskilt under RCP 4.5 och 8.5. Mellangrödans effektivitet, uttryckt som procentuell reduktion av kväveläckaget jämfört med 90N, ökade något i framtida klimat. Den insådda mellangrödan kunde kompensera både för tidigare skörd av huvudgrödan och ökningar av kvävemineralisering i ett varmare klimat. Skördenivåer skiljde sig inte mellan leden under nuvarande klimat, medan simulerat organiskt markkväve ökade i CC_90N-ledet, men minskade över tid i 90N-ledet både i nuvarande och framtida klimat.

Nyckelord: Kväveläckage, mellangröda, klimatförändringar, mark-växtmodellering, klimatscenarier

Dedication

To my family and friends.

"The ingenuity that has been used to feed a growing world population will have to be matched quickly by an effort to keep the nitrogen cycle in reasonable balance" (C. C. Delwiche in 1970)

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Nimblad Svensson, D., Aronsson, H., Jansson, P.-E. & Lewan, E. (2025). Insights gained from modeling grain yield, nitrate leaching, and soil nitrogen dynamics in a long-term field experiment with spring cereals on fertilized and unfertilized soil over 35 years. Field Crops Research, 326, 109856. https://doi.org/10.1016/j.fcr.2025.109856

II. Nimblad Svensson, D., Aronsson, H., Norberg, L. & Lewan, E. (2026). 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. Agriculture, Ecosystems & Environment, 397, 110090. https://doi.org/10.1016/j.agee.2025.110090

III. Nimblad Svensson, D., Aronsson, H., Jansson, P.-E., Kjellström, E., Manzoni, S & Lewan, E. (2026) Modelling nitrogen dynamics and nitrate leaching in spring cereal systems with and without cover crops under future climate scenarios in south-west Sweden. (manuscript)

All published papers are published open access.

The contribution of David Nimblad Svensson to the papers included in this thesis was as follows:

I. Planned the study together with the co-authors. Performed the model simulations and data analysis. Prepared the manuscript with assistance from the co-authors

II. Planned the study together with the co-authors. Performed the data analysis. Prepared the manuscript with assistance from the co-authors

III. Planned the study together with the co-authors. Performed the model simulations and data analysis. Prepared the manuscript with assistance from the co-authors.

1. Introduction

Agricultural production relies heavily on the use of inorganic and organic fertilisers to achieve satisfactory yields. Nitrogen (N) is an important nutrient in cereal crops. Since the invention of the Haber-Bosch process, patented in 1918, mineral N fertiliser has been produced and used in increasing amounts (Erisman et al. 2008). This has caused environmental issues, not least eutrophication of lakes and seas which has been recognised as a problem since the early 70's (Delwiche 1970; Ahl & Oden 1975; Boesch et al. 2001).

The N contained in soils in the form of soil organic nitrogen (SON) is sometimes disregarded. It is built up from organic matter inputs and its contribution to crop N uptake can be more than half of the total amount (Thomsen et al. 2003). Indeed, in non-arable land, indigenous stores of soil N are the primary source of N along with aerial deposition. Thus, historical land management and vegetation greatly influence the fertility of the soil. For example, Mollisols, which include the American prairies and Eurasian steppes, are among the most fertile soils in the world due to their large reserves of SON, built up over a long time (Labaz et al. 2024).

Agriculture contributes to the eutrophication of aquatic and marine ecosystems through the leaching of nitrogen and phosphorus from arable land. Both fertiliser N and mineralisation of SON can result in an accumulation of nitrate-N in the soil which is easily lost through leaching. This is especially true for sandy soils (Cameron et al. 2013). Cover crops (CCs) can be used to prevent excess soil mineral N from being lost (Jarvis et al. 2011). CCs are grown either together with a main crop (i.e. under-sown) or sown after the main crop has been harvested. Cover crops became widely discussed in the 1980's and many field experiments were started to learn more about how CCs could be best utilised (Meisinger et al. 1991; Davies et al. 1996; Hansen & Djurhuus 1997). A review of field experiments in Nordic countries found that CCs reduced N leaching by 43 % on average (Aronsson et al. 2016).

The influence of climate and climate change is directing renewed interest in cover crops for reasons beyond N leaching. One reason is that cover crops can increase soil organic matter stocks (Poeplau et al. 2015), which helps maintain soil fertility and capture CO_2 from the atmosphere (Lal 2004). At the same time, CCs such as oilseed radish (*Raphanus sativus* var. *oleiformis Pers.*) can lead to large N_2O-emissions (Andersen et al. 2025), a very potent greenhouse gas. Another important aspect is the uncertainty about how our currently used CCs will perform under changing climate conditions.

Some long-term experiments initiated in the 1980s in Sweden are still ongoing and provide an opportunity to identify climate change effects that may already have occurred, as well as their impacts on cropping systems with and without cover crops. However, field measurements alone cannot fully describe the temporal dynamics of the components of the nitrogen balance. In particular, the mineralisation and immobilisation of N, which is crucial to any cropping system, is especially hard to study using only measurements (Norberg & Aronsson 2024).

Soil–vegetation models can be used to increase our understanding of agroecosystem behaviour. They can also be used to predict long-term effects of using CCs in different cropping systems (Constantin et al. 2012; Tribouillois et al. 2018; Böldt et al. 2021). With the help of such models, the services and disservices of CCs under current and future climates can be better understood. So far, few modelling studies on the role of CCs under future climate scenarios have been carried out for Nordic conditions. An important goal of this PhD-thesis was to fill that gap by utilising process-based soil–vegetation modelling to study the likely long-term effects of cover crops on nitrogen flows and crop yields within agroecosystems under future climate conditions.

2. Aim and objectives

The overall aim of this PhD-thesis was to improve our understanding of the long-term changes in soil nitrogen dynamics and nitrogen leaching on a sandy soil under present and future climate conditions in cropping systems dominated by spring cereals with and without cover crops (Figure 1). The specific objectives were:

- To compare long-term temporal dynamics in nitrogen mineralisation and soil organic N in treatments with and without fertiliser based on calibrations of a process-oriented model using long-term field data (Paper I).
- To explore differences and potential trends in nitrate leaching and crop yields under recent climate conditions (1989–2023) in treatments with and without cover crops (Paper II).
- To analyse how differences in nitrogen leaching between treatments with and without cover crops may evolve in a changing climate based on long-term soil–vegetation modelling driven by an ensemble of climate scenarios (Paper III)

This thesis is based on a long-term field experiment in Mellby, south-west Sweden, where perennial ryegrass has been grown annually as a cover crop for over 30 years. The soil–vegetation model CoupModel was applied to simulate crops and soil N dynamics. The experiment is included in the programme for long-term field experiments at SLU.

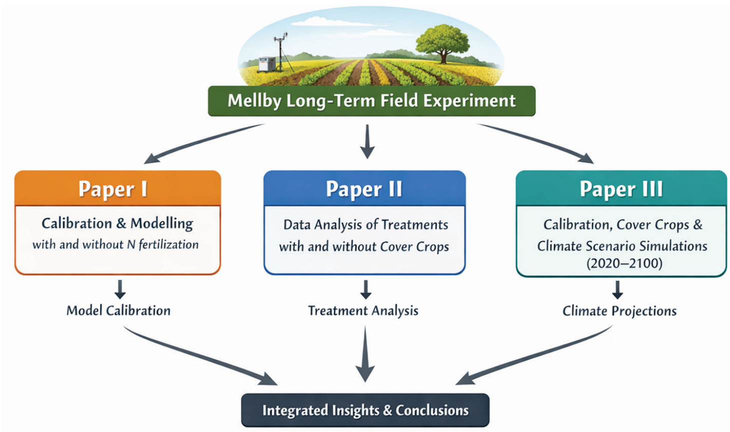

Figure 1. Overview of how the tree Papers in this thesis relate to each other.

3. Background

3.1 Nitrogen leaching in the Nordic countries

In the agricultural regions in the Nordic countries, the soil is often bare after harvest which increases the risk of nitrogen leaching, especially in the southern parts. Denmark stands out as the country with the largest agricultural sector in the Nordic countries with more than 60 % of the land being cultivated. This is also reflected in a larger issue with nitrogen leaching. To reduce nitrogen losses from arable land, cover crops have been widely implemented since the 1990's, especially in southern Sweden and Denmark. The Nitrates Directive of 1991 required member states to define Nitrate Vulnerable Zones (NVZ) where special action is required, such as growing cover crops. These areas cover 22.6 % of Sweden's agricultural area and all of it in Finland and Denmark (Thorsøe et al. 2022). Mitigation programmes implemented in Denmark reduced the national nitrogen losses by nearly 50 % (from 156 to 89 kg N ha^{-1}) in 2014 compared to 1995 (Hellsten et al. 2017). Agri-Environmental schemes compensate farmers that grow CCs in Finland, Norway, Denmark and NVZ-areas in Sweden (Thorsøe et al. 2022). In Denmark it is compulsory to grow cover crops on most farms, while it is voluntary in the other Nordic countries. For Sweden, cover crops have proven to be the most cost-efficient measure to reduce nitrogen leaching from arable land. For the first ten years after the introduction of a governmental subsidy in 1995, cover crops contributed with 25 % to the reduction of N leaching from arable land (Johnsson et al. 2024). In 2023, an additional subsidy was introduced in Sweden for cover crops, with carbon sequestration as the main purpose, without restriction to NVZ-areas. This resulted in a great interest among farmers and the total area used for cover crops increased from 72 000 ha in 2022 to 173 000 ha in 2024 (Blombäck et al. 2025).

3.2 Cover crops shift the N balance

Cover crops reduce nitrate leaching primarily by taking up excess N remaining in the soil after the main crop as well as N from continued N mineralisation during autumn, but also to some extent by reducing water percolation and drainage due to increased transpiration (Meyer et al. 2019).

Thorup-Kristensen et al. (2003) outline many important factors that play a role in the successful implementation of CCs. Among them is the root depth of both the CC and the main crop. If most of the nitrate is found below the roots of the CC, the reduction of N leaching may be negligible. Karlsson-Strese et al. (1996) identified an ideal under-sown CC as one with the following traits. It should i) withstand competition from the main crop, ii) grow slowly until the main crop is harvested, iii) have a well-developed root system, iv) be frost/winter hardy, v) not become a weed easily, and vi) not propagate or transmit pathogens to subsequent crops.

Once the CC has served its purpose and has been terminated and ploughed into the soil, the nitrogen incorporated into its biomass is subject to mineralisation. Cover crops thus effectively convert mineral N into organic N, which partially and gradually becomes available to the next crop (Thorup-Kristensen 1993). Logically, if the timing of N mineralisation is not matched with the uptake requirements of the following crop, it might potentially be lost by leaching instead. In Denmark, it has in general been recommended to incorporate CCs into the soil in the spring to minimise N leaching and to provide N for the next crop. The optimal time of incorporation depends on factors such as soil type, amount of precipitation, and composition of the plant material (Thorup-Kristensen & Dresbøll 2010). For non-legume cover crops, the N contribution to the next crop has often been found to be near zero or even negative (i.e. less available mineral N for the next main crop compared with no CC) (Tonitto et al. 2006). Some Swedish studies found that incorporation in late autumn/winter (November-December) compared with early spring resulted in a positive effect on the yield of the next crop (Wallgren & Lindén 1994; Torstensson 1998) but also that incorporating CCs in spring is preferable to ensure the lowest N leaching, indicating a trade-off (Aronsson & Torstensson 2009). This can be explained by the fact that mineralisation can occur at temperatures as low as +1°C (Van Schöll et al. 1997). However, incorporation in autumn (November-December) often works satisfactorily for reduced leaching if it is done as late as possible before winter (November–December), while incorporation in September or October is less reliable (Aronsson et al. 2011). Thomsen & Hansen (2014) found that the uptake of N was reduced by 50 % when CCs were incorporated early in autumn instead of in winter or early spring, to enable sowing of winter wheat after the cover crop.

3.3 Nitrogen in the organic pool (SON)

Soil organic N is a heterogeneous pool since it can be formed through different pathways and from many different starting materials. It is released through mineralisation, when microorganisms and soil fauna within the complex soil food web decompose soil organic matter (SOM) (Lavallee et al. 2020). There are several protection mechanisms of SOM that alter the speed at which this happens. Most obvious is the chemical recalcitrance which dictates how easily a substance can be decomposed. An extreme example would be organic materials that have gone through partial combustion. Certain plant materials such as waxes or sterols produced by e.g. heather (*Calluna vulgaris*) or lignin-rich wood are also resistant to decomposition. Protection also occurs when OM is occluded in micropores that are so small that decomposers cannot access it (Six et al. 2002; Meurer et al. 2020).

A distinction has been proposed between particulate organic matter (POM) and mineral-associated organic matter (MAOM) (Lavallee et al. 2020). MAOM is largely derived from microbial necromass produced when soil microorganisms assimilate root exudates and subsequently die. MAOM is considered to be relatively well protected through chemical binding to soil minerals. However, the available sites for this type of binding can become saturated. Nevertheless, in agricultural soils, MAOM is commonly dominant. Soils with little POM are often characterised by a low C:N ratio because MAOM is the dominating form of organic matter. A C:N ratio of around 10 is typical for agricultural soils in Sweden (Eriksson et al. 2010). However, some exceptions do exist, for example where the land use history has included heathlands.

3.4 Climate change and its impacts on N dynamics

Warming due to increasing atmospheric CO_2 concentrations is occurring faster in Scandinavia compared with the global mean (Schimanke et al., 2022). It has been warming at about twice the average rate during the 20th century, but this difference is expected to disappear towards the end of the 21st century (Strandberg et al. 2025). Future climate scenarios are commonly described using representative concentration pathways (RCPs), which represent different trajectories of greenhouse gas concentrations in the atmosphere. The main effects in southern Sweden, based on climate anomalies between 1971–2000 and 2071–2100 under scenario RCP 4.5, will be a doubling of summer days (daily maximum temperature above 20 °C) and a decrease in the number of frost days by 20–50 %. Daily minimum and maximum temperatures are projected to increase by approximately 3 and 2 °C, respectively. Precipitation in southern Sweden is expected to increase primarily in winter and remain largely unchanged in summer (Strandberg et al. 2025). In addition to long-term climate change, large-scale climate patterns such as the North Atlantic Oscillation (NAO) influence interannual weather variability in Sweden, with positive NAO phases associated with milder and wetter winters that may amplify year-to-year variability in nitrogen losses (Kjellström et al. 2013).

There are multiple impacts of climate change on nitrogen dynamics in cereal cropping systems. Warmer weather increases N mineralisation and increased precipitation leads to a higher transport of nitrate through the soil (Doltra et al. 2014). Higher crop yields could potentially mitigate increased N mineralisation to some extent through greater crop nitrogen uptake, but it is uncertain if crop yields will increase or decrease in the future climate (Tootoonchi et al. 2025). Regardless, increased mineralisation of SON in the post-harvest season can, if the soil is left bare, result in more nitrate leached from the system. Thus, an increasing need for cover crops in areas vulnerable to nitrate leaching is expected. Evidence suggests that the N uptake potential of CCs, such as perennial ryegrass (*Lolium perenne* L.), is higher than is currently seen in most years in our current climate, even under low light conditions (Thomsen et al. 2010). Maintaining a living vegetation during autumn and winter thus seems to be the most promising strategy to reduce N leaching.

3.5 Applications of soil vegetation models

Crop models can be used to gain knowledge about responses to climate change in cropping systems with and without cover crops. Many crop models have been developed and successfully used for simulating monocultures. Cropping systems with rotations and CCs are more complex and therefore more difficult to model (Salo et al. 2016; Böldt et al. 2021). It becomes even more difficult in systems with under-sown CCs due to the complexities of the competition for water, nutrients and light between the main crop and the CC. Thus, only a limited number of models have been developed and tested for the purpose of simulating inter-cropped agricultural systems, such as under-sown CCs (Berghuijs et al. 2020). Brisson et al. (2004) describe the development of the STICS intercropping module, in which understory vegetation is partitioned into shaded and sunlit components according to light microclimates. These microclimates, determined by the radiative balance, drive the model sub-systems. As a result, effects on plant growth as well as water and nitrogen budgets emerge from this light partitioning. Being a one-dimensional model, no horizontal differentiation is considered, and root growth is influenced only by penetrability and soil water content dynamics. The N demand of each crop is also considered, and the potential uptake is governed by the root density and depth (Gaudio et al. 2016). Shili-Touzi et al. (2010) used STICS to simulate inter-cropping with winter wheat and red fescue (*Festuca rubra* L.) as CC. They showed that the model was useful for understanding the behaviour of the CCs in the field, especially since measurements do not cover all the variables of interest. They also used it to study the optimal emergence of the red fescue to increase N acquisition on the one hand and maintain crop yield on the other.

Manevski et al. (2015) used the DAISY model to simulate maize inter-cropped with red fescue as a CC in Denmark. In DAISY, a composite canopy consisting of the leaf area distributions of the crops is used and the contribution of each crop to the total leaf area index determines the competition for light in each of the layers. As in STICS, the competition for water and N is determined by rooting depth and distribution and is limited by available soil N. The authors found the model to be useful for exploring inter-cropping systems despite discrepancies between simulations and measurements. For instance, major differences were found for maize dry matter and N content under inter-cropping on a coarse sand when following a grass-clover mix. The authors attributed these errors partly to model inaccuracies in the description of red fescue growth and the dynamics of the added organic matter pool when grass-clover was grown prior to the maize. Rashid et al. (2021) simulated 20 different crop rotations at different locations using the DAISY model, including CCs of under-sown ryegrass and oilseed radish. They found that under-sown ryegrass reduced N leaching by up to 54 %. Moreover, above a certain threshold, an increase in precipitation did not lead to more N leaching in their simulations, since percolation was no longer a limiting factor.

The APSIM model was recently used to simulate under-sown leguminous CCs in Sweden (Lagerquist et al. 2024). It has also been used for other intercropping situations. For example, Bartel et al. (2020) used the model to simulate a maize crop grown together with two types of perennial CCs in the U.S. Other examples of intercropping combinations include wheat–faba bean (Berghuijs et al. 2021), sorghum–cowpea (Chimonyo et al. 2016) and maize–wheat as well as maize–field-pea (Knörzer et al. 2011). The canopy module in APSIM simulates the inter-specific competition for light between the crops based on a modified version of Beer's law.

CoupModel (CoupModel, 2026) was used in this thesis due to its ability to describe processes relevant under Nordic conditions, including snow, freezing and thawing as well as tile drainage. Early predecessors of the CoupModel (SOIL-SOILN and SOILN-DB) were applied to represent under-sown CCs with spring cereals in Sweden (Lewan 1993; Lewan 1994; Blombäck et al. 2003; Collentine & Johnsson 2013). However, these model versions included simpler or more static growth modules. The present version of CoupModel has a highly flexible structure and includes dynamic growth modules, which can facilitate simulation of more than one vegetation layer and multiple canopies (CoupModel, 2026). Conrad & Fohrer (2009) applied the model to a crop rotation consisting of winter wheat with under-sown red clover, followed by two years of red clover. In the first period, both discharge and nitrate leaching were simulated satisfactorily (Nash–Sutcliffe model efficiency coefficient (NSE) of 0.73 and 0.49, respectively). The second period, with only red clover showed a poorer agreement (NSE 0.01 and 0.31 for discharge and nitrate leaching, respectively). This was likely due to some inadequacy in the parameterisation. Nevertheless, the potential for using CoupModel to model under-sown CCs was demonstrated.

The aforementioned and described models all seem capable of the task of simulating under-sown CCs. The reason for the small number of studies carried out for these specific CCs might therefore not reflect a lack of model development, but rather a smaller interest (globally) in under-sown CCs compared to those sown after harvest. Indeed, most work has been done on CCs sown after the harvest of the main crop. STICS has been used extensively to assess optimal emergence and destruction dates of CCs to reduce nitrate leaching (Constantin et al. 2015), predict the efficiency of CCs in reducing nitrate leaching (Constantin et al. 2015; Yin et al. 2020), and to investigate how CCs affect greenhouse gas balances and water balances

(Tribouillois et al. 2018). Böldt et al. (2021) used APSIM to simulate a two-year crop rotation in northern Germany, with white mustard as a CC sown after harvest of spring wheat in the first year and after harvest of field peas in the second year in northern Germany. They found good agreement between measured and simulated CC yields ($R^2 = 0.86$, slope = 1.02), total dry matter ($R^2 = 0.43$, slope =0.99) and temporal N uptake (R^2=0.73, slope= 0.81). N leaching was however underestimated by the model. Teixeira et al. (2021) used APSIM to study N leaching in the future climate of four regions in New Zealand under different RCPs. For the purpose of supporting model development, Müller et al. (2006) used DAISY to simulate different CCs following peas as a cash crop. Peltre et al. (2016) used DAISY to explore the effects of straw removal, earlier sowing of winter wheat and the cultivation of oilseed radish as a CC on N leaching, N_2O emissions and soil C stocks.

4. Material and methods

4.1 Field site and management

The Mellby field trial (R0-8403) was established in 1983 with a focus on N leaching under different N fertilisation regimes, cover crops and tillage practices in a spring-cereal dominated crop rotation. The field site is in south-west Sweden (lat. 56° 29' N, long. 13° 00’ E, alt. 10 m) where the climate is cold temperate and semi-humid. The annual mean temperature was 8.2 °C and precipitation 812 mm from 1984 to 2018 SMHIGridClim (Andersson et al. 2021). The soil is developed in sandy deposits (90–130 cm in thickness) underlain by a nearly impermeable glacio-fluvial clay (Johnsson 1991). The topsoil is a sandy loam with a clay content of 5–10 %, an organic matter content of 5.9 % and a total N content of 0.15 % (Table 1). There are 14 plots, each of which is 40x40 m in size and individually drained, of which eight were used in this thesis. Drainage pipes are installed at a depth of 0.9 m.

Table 1. Soil properties at Mellby

	Particle size distribution (%)				
	Clay (< 2 µm)	**Silt (2–60 µm)**	**Sand (60 µm–2 mm)**	**Organic matter content (%)**	**pH**
Topsoil (0–23 cm)	10.4	10.2	79.4	5.9	6.2
Subsoil (23–45 cm)	2.9	2.3	94.9	0.4	5.7

The main crop has mostly been spring-sown cereals, and a simple rotation of oats, barley and wheat has been followed since 2006. Crops that were also grown before 2006 included potato (1987,1992,2002), oilseed rape (1984, 1995, 2004) and triticale (2005). The straw from the cereals was harvested, while straw from rape and potato haulm were left in the field.

Plots with and without N fertilisation (mineral fertiliser) and with and without cover crops were studied in this thesis. Fertilised treatments received 90–110 kg N ha^{-1} yr^{-1}. All treatments, including the unfertilised treatments received 20 kg P and 64 kg K ha^{-1} yr^{-1} until 2009. Thereafter, P and K were no longer applied to the unfertilised treatments. Sowing took place in April–May and harvest in August–September. Plots with cover crops were ploughed in March–April whereas the other plots were surface cultivated in September and mouldboard ploughed in November. The treatments have not been entirely consistent through time (Table 2). In the data analysis in Paper II, we considered plots 2, 11 and 12 (90N) as well as 10,13 and 14 (CC_90N) to be replicates although only two out of the three plots (11,12 and 13,14) are strictly so. In Paper I, data from plots 2 (90N) and 7 (0N) were used in the model calibration and simulations. In Paper III we used the measurements from plot 2 (90N) and plot 10 (CC_90N) to first calibrate the model before running scenario simulations for a future climate.

Table 2. Experimental set-up in the eight plots for the four treatments (90N = 90 kg nitrogen (N) fertiliser ha^{-1} yr^{-1}, CC = cover crop, 0N = no fertilisation) 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) (Paper II).

	Treatment	**90N**	**90N**	**CC_90N**	**CC_90N**	**CC_0N**	**0N**
Year	Plot no	2	11,12	10	13,14	5	7
1984-1988	Cover crop			No CC	Not started	No CC	
	Tillage	Sep	Sep	Sep		Sep	Sep
1988	Cover crop			No CC	Italian ryegrass	No CC	
	Tillage	Sep	Sep	Sep	Mar-Apr	Sep	Sep
1989-1990	Cover crop			Italian ryegrass	Italian ryegrass	Italian ryegrass	
	Tillage	Sep	Sep	Mar-Apr	Mar-Apr	Mar-Apr	Sep
1991	Cover crop			Perennial ryegrass	No CC	Perennial ryegrass	
	Tillage	Sep	Oct	Mar-Apr	Oct	Mar-Apr	Sep
1992-1998	Cover crop			Perennial ryegrass*	Perennial ryegrass	Perennial ryegrass*	

	Treatment	90N	90N	CC_90N	CC_90N	CC_0N	0N
	Tillage	Sep	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Sep
1999-2005	Cover crop			Perennial ryegrass*	Perennial ryegrass*	Perennial ryegrass*	
	Tillage	Sep	Nov-Dec	Mar-Apr	Nov-Dec	Mar-Apr	Sep
2006-2009	Cover crop			Perennial ryegrass	Red fescue	Perennial ryegrass	
	Tillage	Sep	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Sep
2010-2023	Cover crop			Perennial ryegrass	Perennial ryegrass	Perennial ryegrass	
	Tillage	Sep	Sep	Mar-Apr	Mar-Apr	Mar-Apr	Sep

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

4.2 Field measurements and analyses

The flow rate of drainage water from each individual plot was determined in an underground measurement station by tipping bucket flow gauges. Between 1984–1998 water samples were collected by grab sampling every two weeks when drainage occurred. Subsequently, this was replaced by flow-proportional water sampling, in which 15 ml samples were pumped into plot-specific bottles for every 0.2 mm of drainage water entering the measurement station. Subsamples of the water in these bottles were sent for analysis every two weeks after which they were emptied and filled once again. The samples were processed at different laboratories at the Swedish University of Agricultural Sciences (at the Department of Soil and Environment until 2014 and subsequently at the Department of Aquatic Sciences and Assessment). Until 2012, both total N and nitrate-N (NO_3-N) were analysed in the drainage water. In both Paper I and Paper III, data on

NO_3-N was used for model calibration. To this end, linear regression was used to establish a relationship between NO_3-N and total N. It was found that NO_3-N comprised 90 % of the total N in solution (intercept locked to zero, $R^2 = 0.992$, p-value <2.2e-16). For flow-proportional water sampling, daily concentrations were simply the concentration representative of that (2-week) period. With grab-sampling, linear interpolation was applied between sampling events to calculate daily values. To calculate NO_3-N leaching and total N leaching, the daily concentration was simply multiplied by the daily discharge. Mean annual concentrations were also obtained by dividing annual accumulated leaching (total-N or NO_3-N) by annual drainage.

Soil samples were taken at 0–30, 30–60 and 60–90 cm depth on three occasions in most years (before fertilisation in spring, directly after harvest and before ploughing in autumn). Nitrate-N was analysed colourimetrically after extraction with 2 M KCl. These measurements are shown and evaluated in Paper II.

Grain and straw of the main crop were harvested in three sub-plots 20m^2 in size. The dry mass was determined after drying at 60 °C and N contents were determined by dry combustion using an elemental analyser (Tru-Mac CN analyser). Samples of CC biomass were taken by hand from three small sub-plots (0.25 m^2) and analysed in the same way as grain yields and straw of the main crop.

4.3 Climate data and climate change scenarios

Climate data over the field site was composed of gridded daily data. For air temperature, relative humidity and precipitation the source was SMHIGridClim (horizontal resolution of 2.5 km) (Andersson et al. 2021) except for the last year (2019) used in Papers I and III, where data for these variables were obtained from nearby weather stations (data provided by FOMA, SLU). In paper II another gridded database, PTHBV (horizontal resolution of 4 km) (SMHI, 2025), was used for the last years analysed (2019–2023). For the modelling (Papers I and III), wind speed and global radiation were also required. These variables were retrieved from ERA5 (horizontal resolution of ~28 km) (Hersbach et al. 2018). For the data analysis in Paper II, monthly values of the NAO index (NAOi) were downloaded from NOAA Climate Prediction Centre (www.noaa.gov).

Projections of future climate are made with global climate models (GCMs) assuming different emission scenarios. An ensemble of models is often used to account for uncertainty in model structures and the 6th IPCC report for instance, is based on the ensemble from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al. 2016). The resolution of such global models is too coarse to be used on a regional scale and therefore the results of these GCMs are downscaled using regional climate models (RCMs). In Paper III the climate ensemble used as driving data for the model consisted of a combination of GCMs and RCMs for three emission scenarios (RCP 2.6, 4.5 and 8.5) all originating from the EURO-CORDEX initiative (Jacob et al. 2014) (Table 3) and provided by the Swedish Meteorological and Hydrological Institute (SMHI). Precipitation and temperature were bias corrected (by SMHI), while windspeed, relative humidity and global radiation were not. Model simulations were also performed using re-sampled historical climate data for 2020–2100 created by randomly selecting 4-year blocks from daily observations between 2000 and 2020. Entire years were sampled together to retain realistic interannual variability and multi-year patterns, while preventing the emergence of a long-term trend. These simulations were run to distinguish climate change impacts on SON development from changes associated with the model approaching a steady state.

Table 3. Climate model ensemble: global climate models (GCMs) and the regional climate models (RCMs) which they were downscaled with (Paper III)

GCM	**RCM (initialisation)**
CNRM-CERFACS-CNRM-CM5	KNMI-RACMO22E(r1i1p1)
ICHEC-EC-EARTH	DMI-HIRHAM5(r3i1p1)
ICHEC-EC-EARTH	SMHI-RCA4(r12i1p1)
MPI-M-MPI-ESM-LR	SMHI-RCA4(r1i1p1)
NCC-NorESM1-M	SMHI-RCA4(r1i1p1)

4.4 Model description, setup and calibration

CoupModel is a dynamic one-dimensional ecosystem model, which describes the governing processes for water-heat-carbon-nitrogen flows in the soil–plant–atmosphere continuum in response to weather and climate. The soil is represented by a flexible number of layers and thicknesses. A set of switches allows the user to turn on or off the modules required for the simulation purpose and thus for a flexible setup of the model. The model was developed in Sweden at SLU and at the Royal Institute of Technology (Jansson & Karlberg 2004; Jansson 2012). CoupModel includes the most important feedbacks between plant growth and soil water-, heat-, carbon-, and nitrogen flows (Figure 2) and recently also included the phosphorus cycle (He et al. 2021).

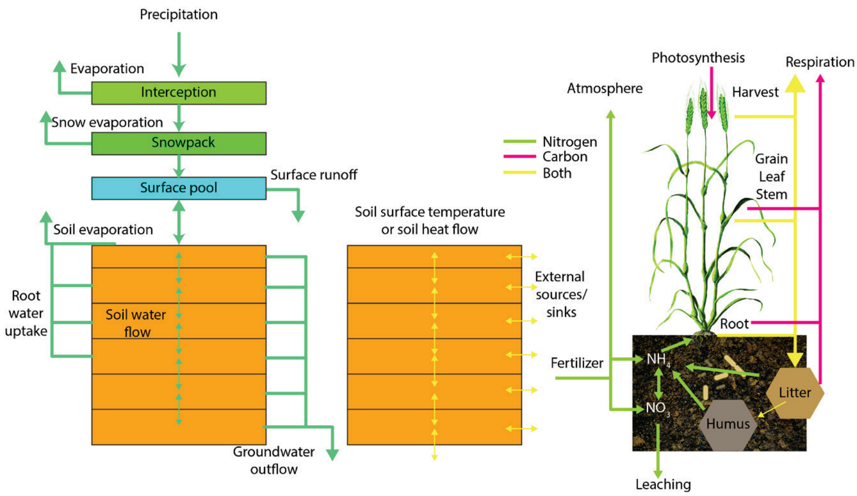

Figure 2. Structure of the CoupModel for water, heat and carbon and nitrogen flows.

CoupModel version 6.2.5 was used in Paper I and version 6.3.1 was used in Paper III. The Brooks and Corey function for water retention (Brooks & Corey 1964) was used and the unsaturated hydraulic conductivity function by Mualem (Mualem 1976). The Hooghoudt drainage equation (Hooghoudt 1940) was used to simulate water flow from drainage pipes. Since the bottom layer was nearly impermeable due to the clay, a seepage equation was used (described in Table S2 in Paper I) to represent the bottom boundary condition for water. The Penman–Monteith equation (Monteith 1965) was used to simulate evapotranspiration. Beer’s law was used to partition net radiation between leaf canopy and soil. The soil profile was divided into twelve layers of 5, 10, 15, 20, and 30 cm at depths of 0–5, 5–15, 15–90, 90–110 and 110–230 cm, respectively. The abiotic environment (i.e. the water and heat flows) interacts with plant growth and the carbon and nitrogen in the soil. The plant growth is based on an "explicit big leaf" approach, which means that the entire canopy is considered as a single leaf. The four growth stage indices (GSI) used by the model are emergence, grain filling, maturation and harvest. These can either be calculated as a function of temperature sums, given as day-number inputs, or based on a combination of both. In Paper I, sowing, emergence and harvest dates were given as input (day numbers, based on actual field data, field management and observations). In Paper III, for the future climate scenarios, new sowing dates were calculated for each climate ensemble file (see below), and emergence and harvest dates were estimated from temperature sums by the model. The maximum GSI for the cover crop was set to 2 (to prevent it from developing grains).

In Paper I, the first year (1984) was run twice to allow the litter pool to stabilise. In Paper III, 1984–1988 was used as spin-up period since CCs were not grown until 1989. The field site is believed to have a history of being a heathland, and a considerable fraction of the SOM was therefore assumed to be inert, as explained in Paper I.

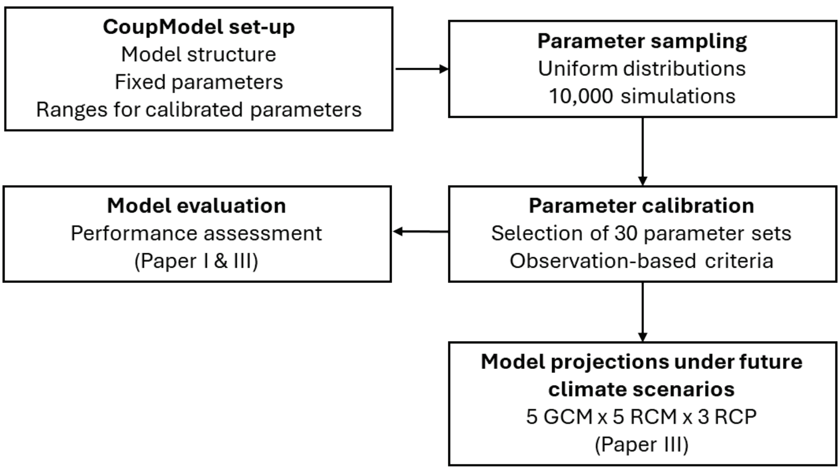

Figure 3. Overview of the modelling process from set-up to calibration (Papers I and III) and model projections driven by future climate scenarios (Paper III).

Model calibrations in Papers I and III were carried out in a similar way and are explained in detail in the respective papers. Briefly, the model was run 10,000 times for each treatment over the entire time-period of available data and with a selection of parameters varying randomly within uniform prior distributions (Table 4). Thereafter, selection criteria (NSE, R^2, RMSE or ME) were applied to filter out model runs which performed poorly for the target variables used (Figure 3). NSE measures model accuracy compared to the mean of observations. Values above 0 indicate that the model predicts better than the mean, 1 is perfect, 0 means the model is as good as the mean, and values below 0 indicate worse-than-mean predictions. Criteria were set manually to achieve as good a fit as possible for the different variables. By setting one criterion at a time, different trade-offs become apparent. Moreover, plotting cumulative distributions made it easy to see how narrow the criteria could be set without losing too many runs. In this way, a balanced and robust calibration was ensured which meant that the model performed reasonably well for each target variable.

Table 4. Parameters used in the calibrations (Papers I and III) and their min and max values

Parameter	Min/ Max	Unit	Function
CLeaftoGrain	0.01/ 0.04	-	Fraction of carbon in leaves reallocated to grains during grain development
CStemtoGrain	0.01/ 0.04	-	Fraction of carbon in stem reallocated to grains during grain development
ConductMax	0.01/ 0.04	m s^{-1}	The maximal conductance of a fully open stomata
CritThreshold Dry	50/ 200	cm water	Critical pressure head for reduction of potential water uptake
DrainSpacing LowerB	10/ 15	m	Distance between assumed drainage system for calculation of deep percolation
NLeaftoGrain	0.02/ 0.05	-	Fraction of nitrogen in leaves reallocated to grains during grain development
NStemtoGrain	0.02/ 0.05	-	Nitrogen flux from stem to grain

NUptFlexibility Deg	0.2/ 1	-	Compensatory N uptake from layers with excess of N
RadEfficiency	1.5/ 3	gDw MJ^{-1}	Radiation use efficiency for photosynthesis at optimum temperature, moisture and C:N ratio
RateCoefHumus	5×10^{-5} 4×10^{-4}	day^{-1}	Rate coefficient for the decay of humus (slow pool)
LeafMassPer Area	10/ 20	gC m^{-2}	Parameter to convert leaf C mass into leaf area
Humfraclitter	0.1/ 0.3	gC gC^{-1}	Fraction of carbon and nitrogen contained in the litter pool of the soil that will enter the humus pool
Parameters only included in paper I			
CNLTh	60/ 100	-	Threshold of C:N ratio in leaves above which no photosynthesis occurs
Flexibility Degree	0.02/ 0.6	-	compensatory water uptake calculated when water deficiency occurs due to excessively dry soil in some layers while water tensions in other layers remain below the critical threshold
Leafc1	0.3/ 0.4	-	Fraction of the mobile carbon assimilates allocated to the new shoots
ThetaLowerRange	5/13	Vol.%	Water content interval in the soil moisture response function for microbial activity, mineralisation-immobilisation, nitrification and denitrification
Parameters related to cover crop treatment			
RadEfficiency(CC)	2/4	gDw MJ^{-1}	Radiation use efficiency for photosynthesis at optimum temperature, moisture and C:N ratio
LeafMassPerArea(CC)	10/20	gC m^{-2}	Parameter to convert leaf C mass into leaf area
NUptFlexibilityDeg (CC)	0.2/1	-	Compensatory N uptake from layers with excess of N

Before running the model with future climate scenarios, the existing climate file used in Paper I and for the calibration in Paper III (1984–2019) was extended by adding climate scenario data for the period 2020–2100 from the CORDEX climate model ensemble. This resulted in 15 continuous climate input time series covering the entire simulation period. For the period from 2020 to 2100, sowing was assumed to take place when the 10-day moving average temperature was equal to 5 °C and the calendar date had passed 1st of March. Fertilisers were also applied in the model on the same date. For CC_90N which was tilled in spring, ploughing was assumed to take place 14 days before sowing and fertilisation. The model was run with 30 accepted parameter combinations for both treatments (spring cereals with and without a cover crop), resulting in a total of 900 model runs (30 parameter combinations, 5 GCM–RCMs, 3 emission scenarios, 2 treatments).

4.5 Statistical analysis

Several statistical analyses were applied to evaluate both the measured data, climate data and model outputs. Mann–Kendall tests were performed to check for monotonic trends in the climate data in Papers I and II and model outputs and measured variables in Papers I and III. Because Mann–Kendall only tests for monotonic trends, a more flexible approach was also used in Paper II. A generalised additive model (GAM) was used to find directional changes in mean annual concentrations and total N leaching (see Paper II for more details). Yearly differences in N leaching between CC_90N and 90N were tested with t-tests. A Spearman correlation analysis was performed to find relations between temperature, precipitation or NAO index (NAOi) and N variables. In Paper III, a mixed effects model was used to compare differences between CC_90N and 90N with respect to different RCPs and two time periods (2040–2070 and 2070–2100). All analyses were carried out for data summarised (mean or sum) by calendar years in Papers I and III and agro-hydrological years (1st July – 30th June) in Paper II.

5. Results

5.1 Climate, hydrology and climate change data

Temperature increased significantly over the period 1989–2023 with a Theil Sen's slope of 0.05, indicating a yearly increase of 0.05 °C. No trend was detected for precipitation. NAOi was significantly correlated to both temperature and precipitation (Paper II). The annual drainage, determined for the period from 1 July to 30 June, averaged 281 mm, with observed values spanning from a minimum of 41 mm in 2020/2021 to a maximum of 499 mm in 1998/1999 (Figure 4). There was no monotonic trend over time. Furthermore, there were no significant differences in mean annual drainage between plots with cover crops and those without, in any of the years examined. Most of the drainage occurred between August and April (Figure 4).

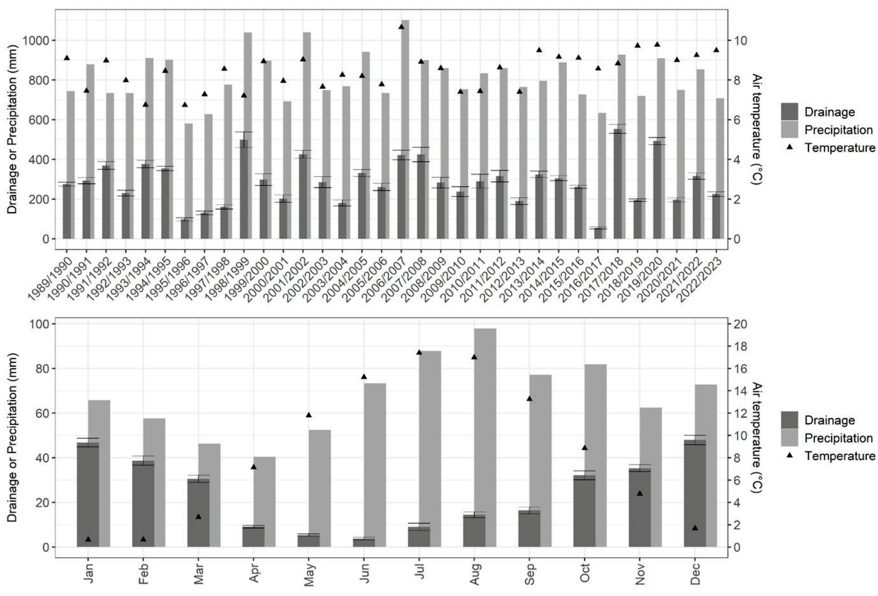

Figure 4. Mean annual (top panel) and monthly (bottom panel) precipitation (mm), air temperature (°C) and discharge (mm) for the eight plots used in Paper II over the years 1989–2023. Bars show standard errors for the eight plots.

In the Climate change scenarios, there was a clear increase in temperature in all models which was especially large for RCP 8.5 (Figure 5). The direction of change for precipitation varied across models, months and emission scenarios. For RCP 8.5, the autumn and winter precipitation increased in all but one model (Figure 5).

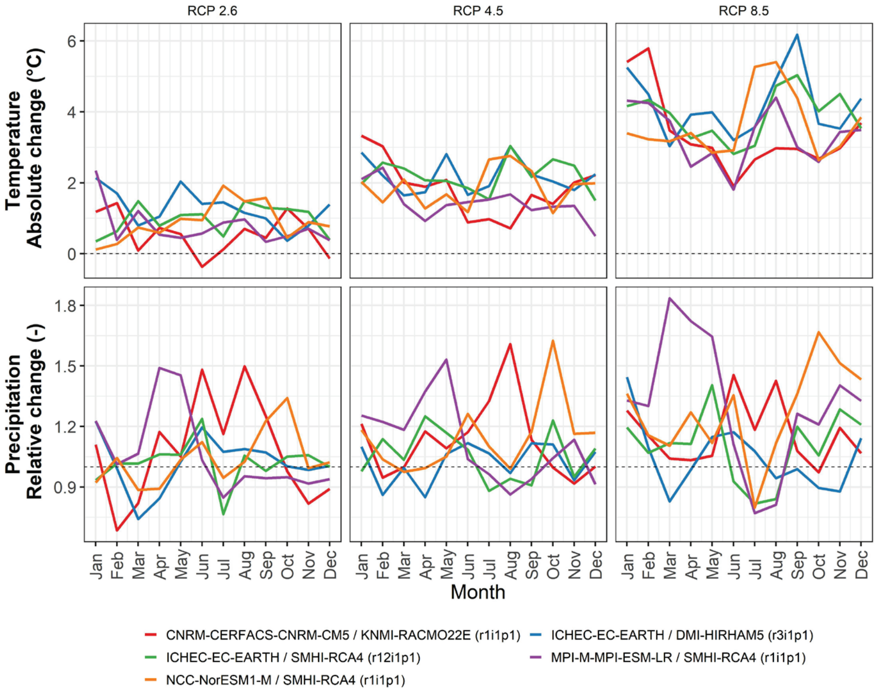

Figure 5. Monthly climate anomalies of temperature (top panel, expressed as differences between future and reference periods) and precipitation (bottom panel, expressed as relative change, future/reference) for the period 2071–2100 relative to the 1981–2010 baseline. Columns correspond to different greenhouse gas scenarios (RCP 2.6, RCP 4.5, and RCP 8.5). Each coloured line represents a different climate model. Dashed horizontal lines indicate no change.

5.2 Model calibration and validation (Papers I and III)

5.2.1 Constrained parameter ranges

Although CoupModel had undergone some updates between Papers I and III, and slightly different calibration criteria were used in Paper III, the posterior parameter ranges obtained were still similar in the 90N treatment (Figure 6). Nevertheless, *RadEfficiency* was higher in 90N and CC_90N in Paper III compared to 0N and 90N in Paper I. Some significant differences in derived parameter values were also found between treatments. For example, *NuptakeFlexibilityDeg* (Compensatory N uptake from layers with excess of N) was highest in CC_90N and smallest in 90N. *RateCoefhumus* (Rate coefficient for the decay of humus (slow pool)) was significantly higher in 0N compared to the other two treatments, for which it was significantly higher in CC_90N compared with 90N.

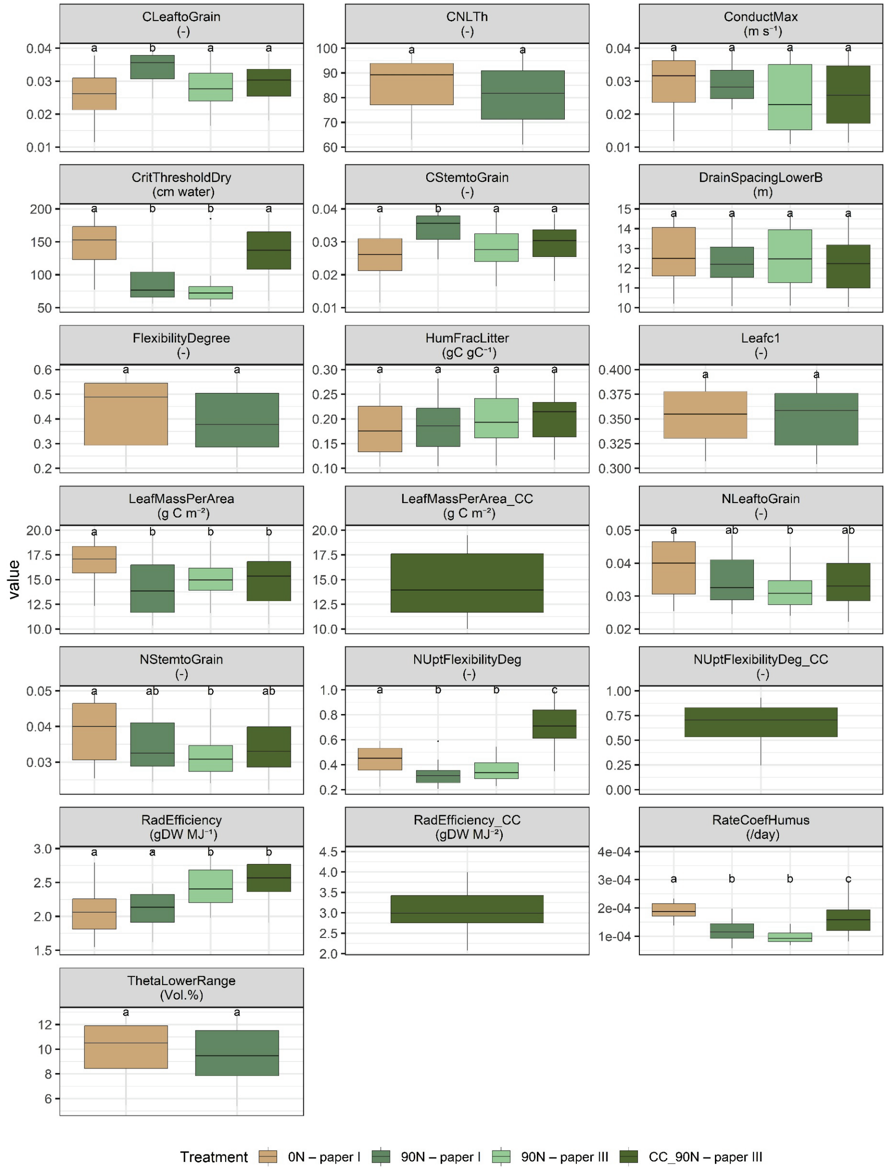

Figure 6. Posterior parameter ranges after calibration for the unfertilised (0N), fertilised (90N) and cover crop treatment (CC_90N). Horizontal lines inside boxes indicate median values and vertical lines show min and max parameter values after selection of the 30 accepted parameter-sets for each treatment. The min and max values on the y-axis are the min/max of the prior distributions. Letters indicate significant differences between treatments (Tukey HSD, P-value <0.05).

5.2.2 Model performance

Although calibrations greatly reduced bias for all treatments (see Papers I and III), model performance differed between treatments for the different variables used in the calibrations (Table 5). There were also differences in performance for the fertilised treatment (90N) between Papers I and III due to a combination of changes in model structure and calibration strategy. Generally, the performance was better for 90N in Paper III compared with Paper I, except for N content in harvested grain and drainage. The model performed better for 90N compared to CC_90N for all shared variables.

Table 5. Mean Nash-Sutcliffe efficiency for 30 accepted parameter sets and standard deviation for the different model calibrations. CC = cover crop

	Unfertilised (0N)	**Fertilised (90N Paper I)**	**Fertilised (90N Paper III)**	**With CC (CC_90N)**
NO_3-N leaching	0.12±0.07	-0.03±0.12	0.43±0.02	0.07±0.03
Drainage	0.65±0.04	0.67±0.04	0.45±0.02	0.40±0.03
Grain yield	0.08±0.17	0.02±0.45	0.24±0.06	0.11±0.07
N in harvested grain	0.02±0.04	0.35±0.16	0.17±0.04	-0.30±0.20
Aboveground harvest	-2.33±0.32	-0.26±0.40	0.05±0.16	-0.13±0.18
N total harvest	-0.16±0.06	-3.5±0.80	-1.53±0.60	-1.85±0.83
CC biomass	-	-	-	-0.69±0.85
CC N content	-	-	-	0.29±0.11

5.3 Mean annual N concentration, soil N and N leaching, N uptake and crop yields (Paper II)

Both mean annual N concentration in drainage water as well as total N leaching were significantly lower in CC_90N compared to 90N (18 and 17 out of 34 years, respectively). The reduction in N leaching was on average 48 % across all years when a cover crop was grown. This effect did not decline with time. Annual mean total N leaching was 18.6 ± 1.4 and 33.9 ± 1.6 kg N ha^{-1} for CC_90N and 90N, respectively, and 10.2 ± 1.8 and 16.7 ± 1.7 kg N ha^{-1} for CC_0N and 0N when averaged across the whole experimental period. Yield and drainage did not differ between CC_90N and 90N. The GAM indicated a significant increasing trend in mean annual N concentration for all three replicates of 90N and for the single 0N plot, all starting shortly after 2010 (Figure 7). No such trends were found in the treatments with cover crops.

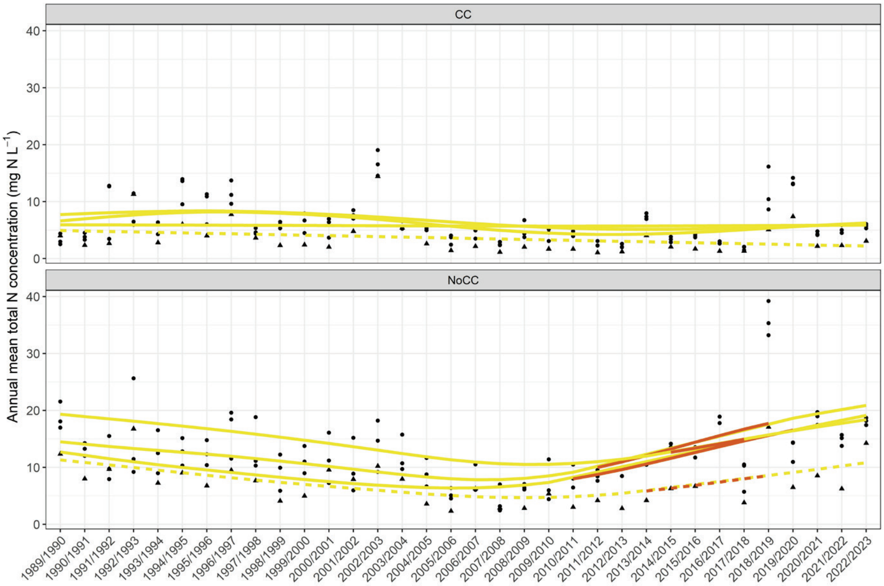

Figure 7. Generalised additive model (GAM) fit to total nitrogen (N) concentration (mg L^{-1}) in drainage water for field plots with cover crop (CC, top panel) and without cover crop (NoCC, bottom panel), one line per replicate. The dashed lines and triangles represent the unfertilised treatments. Red colour indicates a significant increasing trend (Paper II).

The above-ground biomass of cover crops and weeds at incorporation averaged 980 ± 94.8 kg ha^{-1} for CC_90N, with values ranging from 26.1 to 1870 kg ha^{-1}. The amount of N contained in the cover crops averaged 17.8 ± 1.6 kg N ha^{-1} and ranged between 1.1 and 48.5 kg N ha^{-1} on an annual basis.

Soil nitrate was significantly lower in CC_90N compared to 90N at harvest, in late autumn and in spring (Figure 8). The unfertilised treatment (0N) appeared to have a higher soil nitrate than CC_90N in both late autumn and spring, although this could not be tested statistically due to the lack of replicates in the 0N treatment.

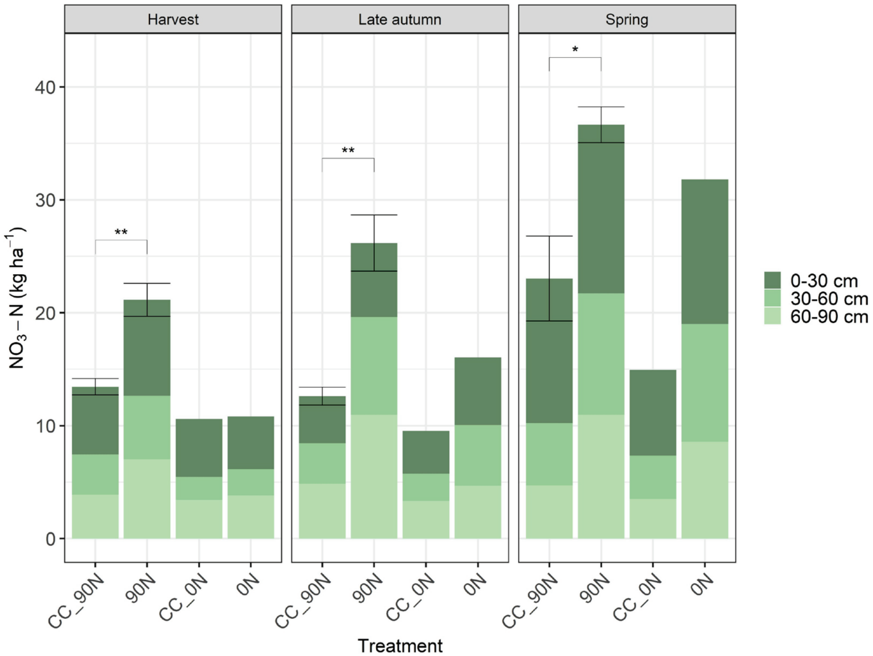

Figure 8. Mean soil nitrate nitrogen (NO_3-N, kg ha^{-1}) in treatments with and without an under-sown cover crop and fertilisation (n=3 for CC_90N and 90N, n=1 for CC_0N and 0N). Samples were taken at three sampling periods (at harvest, in late autumn and spring) over 34 years, at three soil depths (0–30, 30–60 and 60–90 cm). Error bars represent standard error for the whole profile. Stars represent significant differences between fertilised treatments for the whole profile (*=$p<0.05$, **=$p<0.01$) (Paper II).

5.4 Climate impact on N variables between 1989–2023 (Paper II)

Spearman rank correlation analysis indicated some significant correlations between NAOi, precipitation and temperature and the different N variables analysed (Figure 9). In CC_90N, precipitation was positively correlated with total N leaching, and NAOi was negatively correlated with soil nitrate in spring and positively correlated with N content in cover crop biomass. In 90N, precipitation was negatively correlated with soil nitrate in spring and total N concentration in drainage water and positively correlated with total N leaching. Temperature was positively correlated with total N leaching, while NAOi was positively correlated with both soil nitrate contents in autumn, and total N leaching.

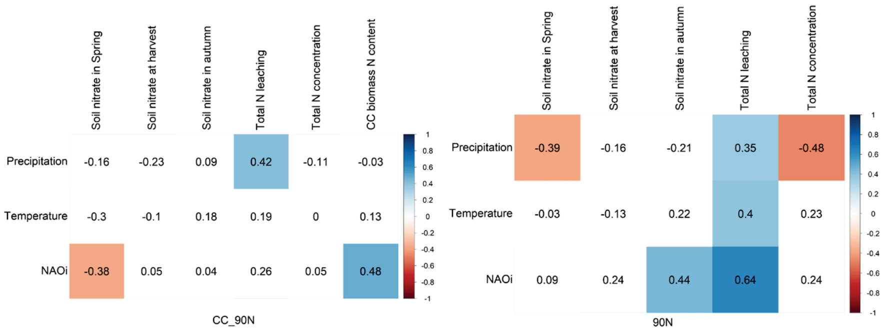

Figure 9. Spearman rank correlation coefficients (ρ) for relationships between nitrogen (N) variables and weather variables for the treatments with and without cover crop, CC_90N (left) and 90N (right). Significant correlations ($P < 0.05$, $n = 34$) are highlighted in red (negative) or in blue (positive). All variables except soil nitrate and CC biomass N content were summarised for agrohydrological years (1 July–30 June). Total N concentration refers to the concentration in drainage water, Spring refers to March–May and autumn to September–November (Paper II).

5.5 Nitrogen flows in systems with and without a cover crop in a changing climate (Paper III)

Drainage increased during 2020–2100 in the treatment without cover crops for most climate models for RCP 4.5 and 8.5 (3 of 5 and 4 of 5, respectively). In the treatment with cover crops, drainage also increased for 3 of 5 climate models for RCP 4.5 and 8.5 (Figure 10). The climate models generating the highest increase in simulated drainage also generated the highest increase in simulated N leaching for the 90N treatment. N leaching was predicted to increase significantly for 90N with all climate models for RCP 4.5 and 8.5. For CC_90N, fewer climate models projected increases in simulated N leaching for RCP 4.5 and 8.5 (4 of 5 and 3 of 5, respectively). One striking result for CC_90N was an increase in N mineralisation, which occurred in all simulations with all climate models for both RCP 4.5 and 8.5. N uptake by the cover crop was also projected to increase drastically. Grain harvest and N uptake in grain generally decreased for both treatments for RCP 4.5 and 8.5. Overall, the above-mentioned effects were greatly reduced in RCP 2.6. However, simulated N mineralisation did increase for 4 of 5 climate models in CC_90N even for this low emission scenario.

Figure 10. Mann–Kendall trend tests performed across all model runs for the treatments with (CC90N) and without (90N) cover crops during 2020–2100. The intensity of the colour indicates the Median Kendall's T and the numbers Theil Sen's slope (Paper III).

The effects of the different RCPs are projected to increase towards the end of the century (2070–2100) compared to mid-century (2040–2070) for most of the target variables (Figure 11). Differences between the treatments also increased, especially for N mineralisation and nitrate leaching. The reduction in N leaching by growing a cover crop ranged between 20 and 80 % across all climate models and RCPs for the two periods. It increased from a median of 59 at mid-century to 65 % at the end of the century for RCP 8.5.

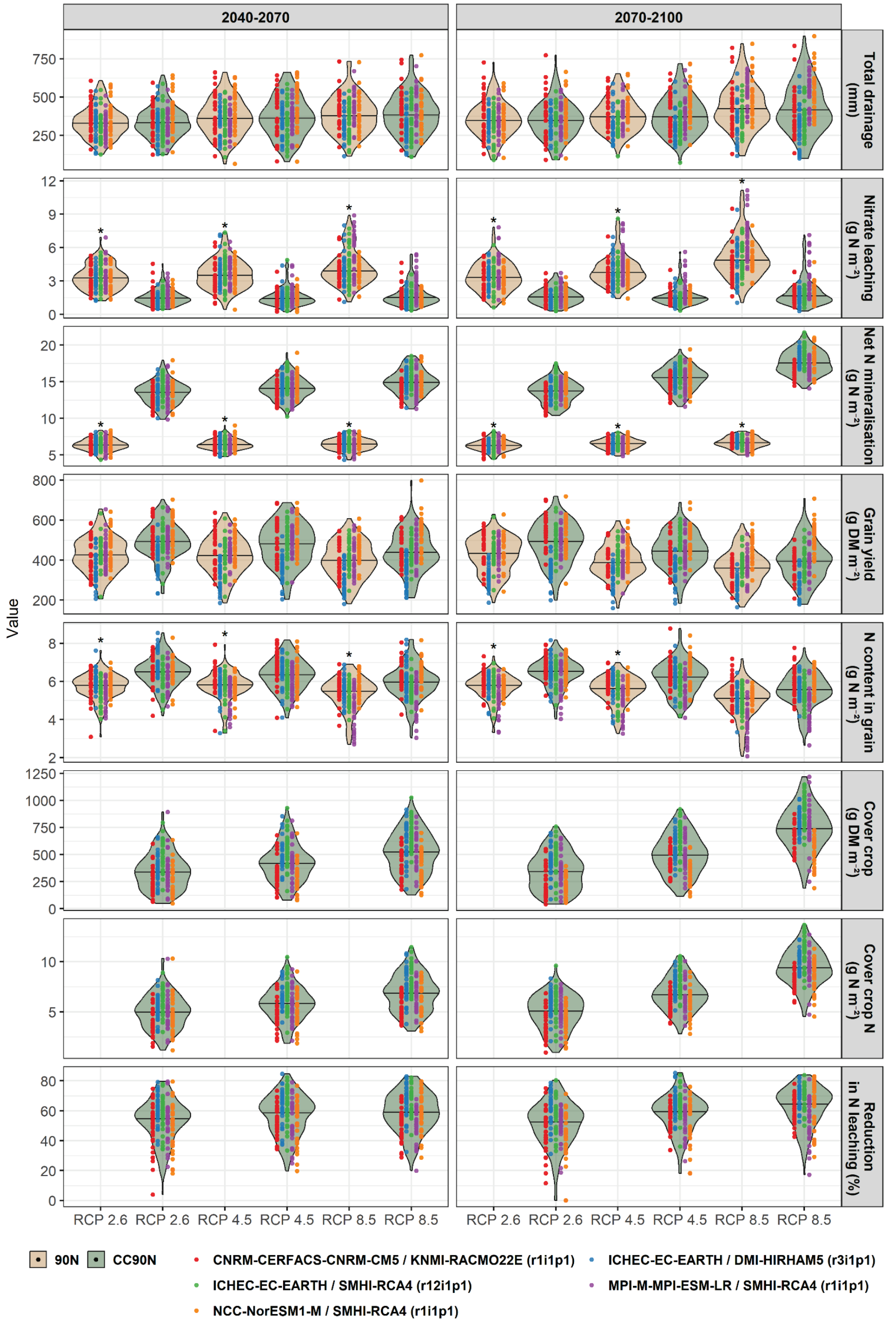

Figure 11. Violin plots for model outputs at mid-century (2040–2070) and end of century (2070–2100) for both treatments. Dots represent the mean of the model runs with the 30 parameter sets for each year and climate model. The horizontal line is the median value for all 30 years and climate models. Stars above 90N denote significant differences between treatments (Paper III).

Soil organic nitrogen was projected to increase in CC_90N for all climate models and emission scenarios according to the median of the model runs with the 30 parameter sets (Figure 12). This contrasted with the simulations for 90N, where SON decreased. When the model was run with resampled historical climate, SON largely followed the same pattern, except for RCP 8.5, where the loss was slower towards the end of the century for 90N compared to the simulations with the climate scenarios. For CC_90N, the increase in SON was more or less continuous through time, but in the projections for RCP 8.5 there was a notable increase in SON acquisition beginning around mid-century.

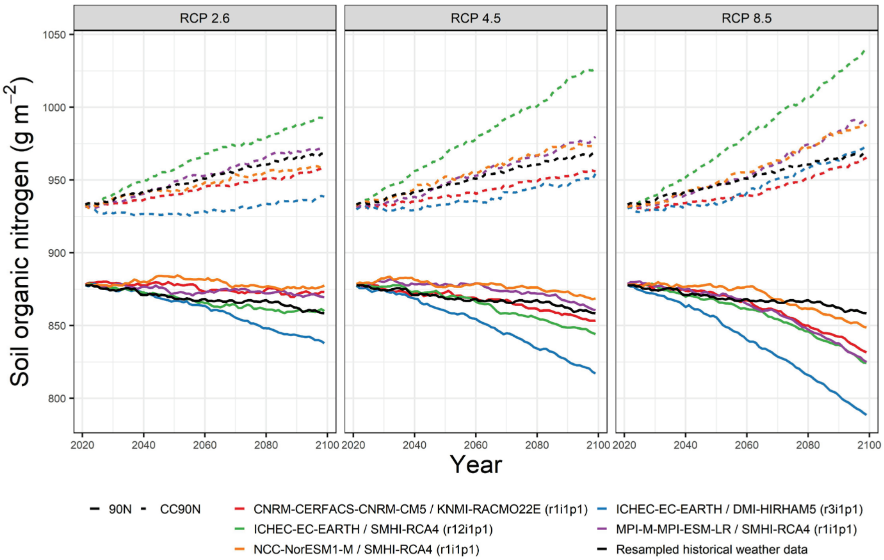

Figure 12. Soil organic nitrogen for 90N (solid lines) and CC_90N (dashed lines) represented as the median of simulations with the 30 best parameter sets, using climate data from five different GCM-RCM models with three different forcings (RCP 2.6, 4.5 and 8.5) as input. The black line is the median of model runs with resampled historical weather data (Paper III).

Harvest occurred progressively earlier in the projections, especially for RCP 8.5 (Figure 13). Although one might expect that the number of days from sowing to harvest would also decrease, this was not always the case (see Paper III). Earlier sowing means shorter and likely also cooler days which means that it takes longer to reach the temperature sum required for maturity.

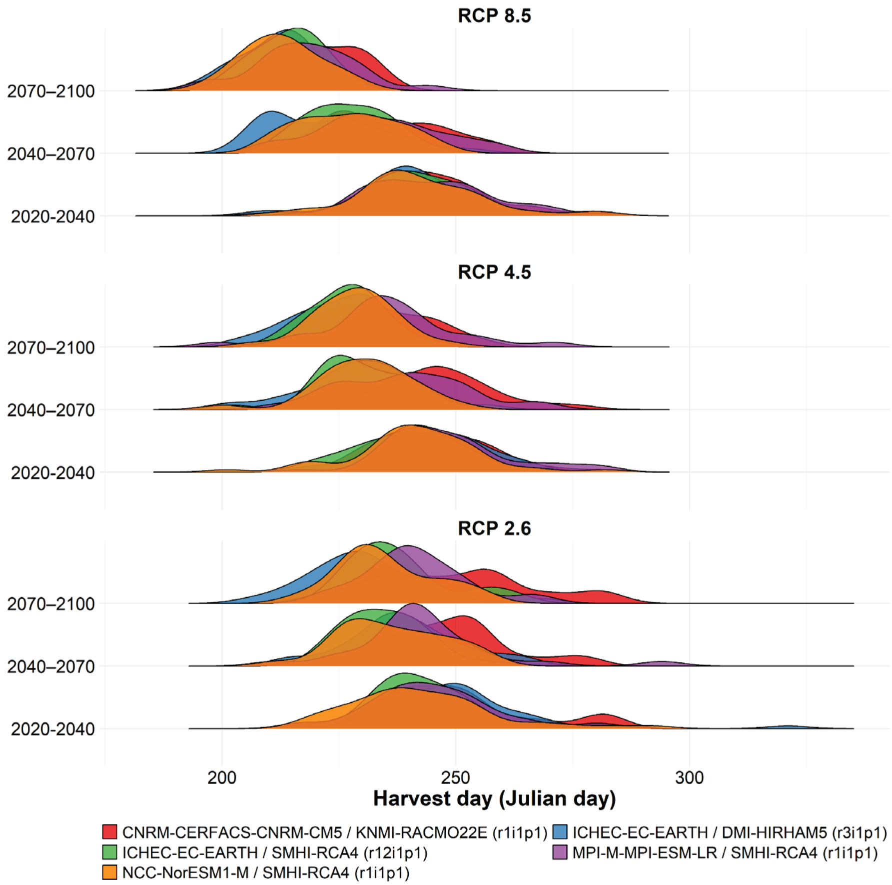

Figure 13. Harvest day distribution for each climate model and for the different RCPs and three time periods. Ridge height indicates the relative density of harvest dates for each period (Paper III).

In the model simulations, the N uptake of the main crop occurs progressively earlier in the year (Figure 14). As the main crop is harvested earlier, the CC has more time to grow without competition and under more beneficial conditions (more light and warmer). Thus, the cover crop starts taking up N earlier and in higher amounts. Towards the end of the century, the main N uptake by the cover crop occurs before September. Yet its daily N uptake in autumn is comparable to that under the current climate or higher and continues for longer.

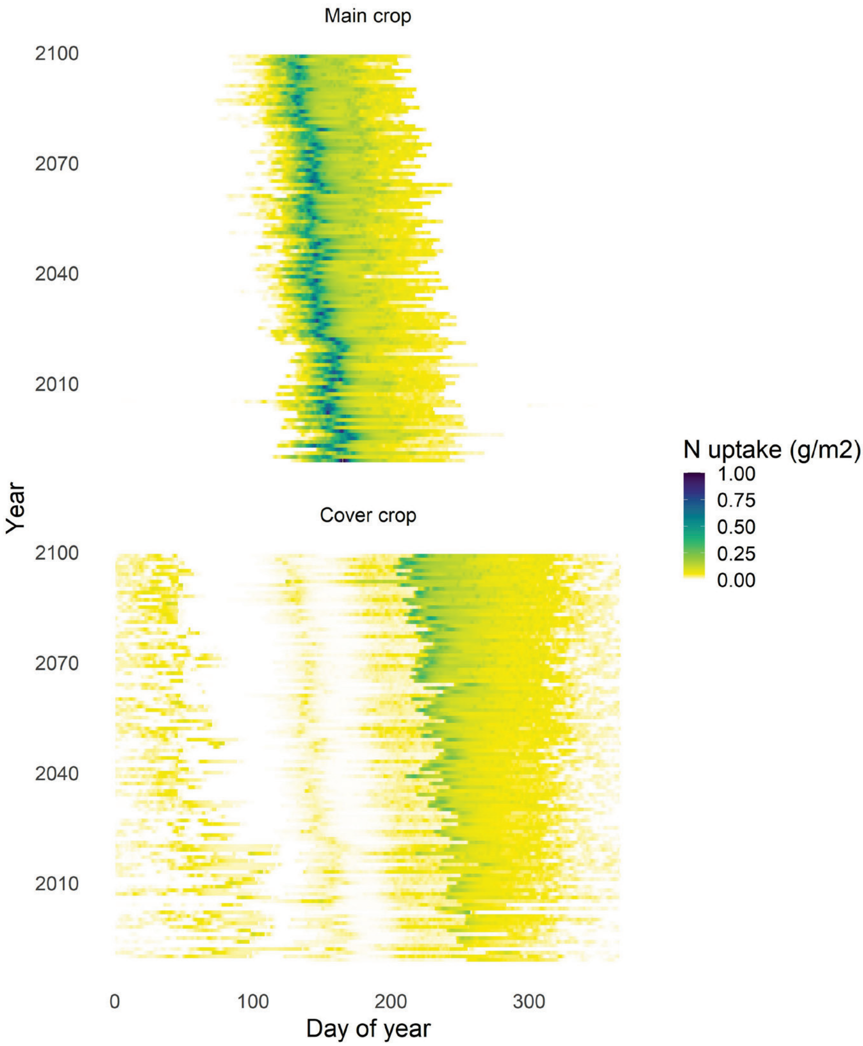

Figure 14. Example of daily N uptake (g N m^{-2}) by the main crop (top panel) and cover crop (bottom panel) for one model run for RCP 4.5 over the whole simulated period (Paper III).

6. Discussion

6.1 Nitrogen mineralisation and soil organic nitrogen

In Paper I, the model suggested a decreasing trend in N mineralisation in the unfertilised treatment, but no trend in the fertilised treatment, for the period 1984–2019. In Paper III, only 1 of 5 climate models suggested an increase in N mineralisation under RCP 2.6 for the fertilised treatment (90N), whereas 4 of 5 climate models did so under both RCP 4.5 and RCP 8.5. In the treatment with cover crops, N mineralisation increased significantly according to 4 of 5 climate models for RCP 2.6 and in all climate models for RCP 4.5 and 8.5. The larger increase in CC_90N can be explained by an increase in SON (Figure 12) resulting from cover crop N uptake and yearly incorporation of cover crop biomass into the soil (Figures 11 and 14). An increase in N mineralisation was also simulated by Willaume et al. (2025) with STICS, when either fava bean or rapeseed was grown as a CC after maize in 2016–2050 for RCP 8.5 in France.

Considering the importance of organic N mineralisation for both N leaching and crop yield (Thomsen et al. 2003), it is of great interest to ensure that model parameters controlling decomposition of organic matter are realistic. The slightly different calibration strategies in Papers I and III did not result in significantly different ranges for the parameter *ratecoefhumus* (Rate coefficient for the decay of humus (slow pool)) in 90N (Figure 6). The calibration for the 0N treatment in Paper I resulted in significantly higher values of this parameter compared to both 90N and CC_90N. This was assumed to be due to changes in microbial function and composition which the model does not consider. For example, N fertilisation may have reduced microbial respiration (Spohn et al. 2016). The parameter range for CC_90N was between 90N and 0N. It is likely that the ploughing in of CCs every year enhanced microbial activity due to the addition of higher substrate quality (Cyle et al. 2016). Thus, with the current model structure, optimal parameterisations will most likely change if management practices such as ending N fertilisation or growing a CC are changed. Since the *ratecoefhumus* parameter in CoupModel plays such an important role in the nitrogen cycle, uncertainty in this parameter explains a large part of the variation in results obtained with the 30 accepted parameter sets.

A common modelling strategy is to calibrate mineralisation rates from 0N plots (e.g. Schwartzkopff et al. 2025). However, the results in Paper I suggest that this can be problematic, since the absence of N fertilisation seemed to speed up microbial respiration. Using a model that accounts for both C and N, as done in this thesis, is preferable to a model with only C since variables such as N leaching and N uptake by crops help to constrain the parameters that affect decomposition. Measurements of root biomass and N content are often missing and would be highly useful in model calibration.

Although not shown in Figure 12, uncertainty in SON was strongly influenced by the individual parameter set. In fact, differences between parameter sets were often greater than between climate models. Wang et al. (2024) found that, in agricultural climate impact assessments, differences in model processes (model structure) and parameters accounted for 52 % and 15 % of the total uncertainty, respectively. Accordingly, comparing results obtained with different models is highly beneficial for investigating structural uncertainty (Constantin et al. 2019). Uncertainty in climate data including the selection of scenarios, climate models, and downscaling and bias-adjustment methods accounted for an additional 17 %.

6.2 N leaching and N uptake in a warming climate

N leaching in the climate change scenarios in Paper III was projected to increase substantially more in the treatment without CCs than in the treatment with CCs. This indicates that there is a risk of increasingly negative impacts on water quality under the current climate warming. The same conclusion was drawn in Paper II, based on the observed treatment responses to temperature and NAOi, as well as the increase in total N concentrations in drainage shortly after 2010 that were only observed in treatments without cover crops (Figure 7). Growing a cover crop is therefore essential to reduce N leaching in the face of climate change (Jabloun et al. 2015). In both treatments in Paper III, N uptake of the main crops decreased with time in the projections. At the same time, N mineralisation increased, especially in the treatment with cover crops. Constantin et al. (2012) and Willaume et al. (2025) also found simulated N mineralisation to increase with time when cover crops were grown year after year. The concomitant decrease in grain yield in this study suggests that lower N uptake by the main crop likely depended on other stressors than N limitation. The increase in N leaching in the treatment without cover crops seems primarily to be due to earlier harvest times and a lower annual N uptake by the main crop, higher N mineralisation and an increase in drainage. This could to some extent be mitigated even without a cover crop by a better use of the longer vegetation period, for example by choosing cultivars which reach maturity more slowly.

6.3 Cover crop performance in the present and future climate

Cover crops effectively took up N from the soil during 1989–2023, with no decline over time in their efficiency in reducing nitrogen leaching compared with the treatment without cover crops (Paper II), and in the climate change projections (Paper III) this efficiency was maintained while nitrogen uptake increased over time. The main explanation that can be inferred from the model simulations is that with climate change, the main crop will be harvested earlier, and therefore the N uptake by the cover crop will also start earlier (when radiation is higher) resulting in a higher total N uptake by the cover crop (Figure 14). The Period during which the CC takes up N in autumn is also longer (when radiation is lower) due to the milder climate, but this contributes much less to the overall N uptake. Both the measurements and simulations indicate that perennial ryegrass can grow and take up much more N in a warmer climate than it does in an average year in the current climate. These results align well with those of Thomsen et al. (2010) who found N uptake to compensate for up to 80 % more N mineralisation with a temperature increase of 8°C during autumn in a pot experiment.

In Sweden, although there is a growing interest in cover crops, the number of species that can be used is restricted in the current climate. A longer period for growth can allow new species to be grown. Moreover, the greater biomass production of perennial ryegrass in the future climate projections makes it potentially interesting to use them for production of fodder or bioenergy (e.g. Barrios Latorre et al. 2024).

6.4 Yield

In Paper I, yields remained stable over time even without N fertilisation due to the high rates of N mineralisation in the Mellby soil. In Paper III, the model projections indicate a decrease in yield and N content in the grain for RCP 4.5 and 8.5 in both treatments. Thus, the increase in SON and N mineralisation in CC_90N only seemed to benefit the cover crop and not the main crop. If a legume was grown instead, more N would likely have been present in the topsoil for the main crop (Quemada et al. 2020). However, growing leguminous CCs can increase N_2O emissions (Kjær et al. 2026). Moreover, accounting for the positive effects of elevated CO_2 on spring cereals (Rezaei et al. 2023) and changes of cultivars could change the outcome. Yield was more affected by the different climate models than by the RCP scenario, which is in line with Corbeels et al. (2018). However, yield decreased with time for almost all climate models and emission scenarios (Paper III). A plausible explanation is that warming accelerates crop development. Simulations with the CERES-Wheat model in Finland found a negative effect of elevated temperatures on yield when elevated CO_2 concentrations were not accounted for (Laurila 2001). Once the effects of CO_2 concentrations and earlier sowing (May 1st instead of May 15th) were included in the simulations, potential grain yield was projected to increase. However, in our projections, sowing took place much earlier (from 1st of March), which meant that more of the plant development occurred during a period with less solar radiation. This in turn restricts photosynthesis, while respiration rates remain high. Therefore, later-maturing cultivars are especially important at higher latitudes (Minoli et al. 2022).

6.5 Uncertainties and assumptions

Like all models, CoupModel has its strengths and weaknesses as well as opportunities and challenges. The development of the model has been focused on making it suitable for representing water-heat-carbon-nitrogen dynamics in a wide range of different ecosystems (including forest, bushes, grass-ley and mires in addition to agricultural crops). Unlike most crop models, crop-specific parameter values have not been systematically derived for different types of crops (e.g. cereals or crop varieties). Thus, no database with crop-specific parameter values is available to users. This presented a challenge, which was met by including some crop-related parameters in the calibrations. Parameter uncertainty was accounted for by identifying 30 acceptable parameter sets for each treatment, which were then used in the long-term modelling. Nevertheless, there is no doubt that the representation of different crops could be further improved. However, such a task was beyond the scope of this thesis and would have required more detailed crop data than is available from the Mellby field experiment. The model performance was better for the treatment without CC in Paper III (Table 5). This was expected, as simulating two crops simultaneously is more difficult (Yu et al. 2024). Therefore, improvements in the representation of undersown ryegrass grown together with a spring cereal would reduce model uncertainty. Furthermore, the effects of increasing CO_2 concentrations could not be considered in these long-term simulations, but should have influenced yields positively (Rezaei et al. 2023).

Using the measured SON and SOC contents as initial values for the humus pool did not work well due to the very high C:N ratio of the soil, which led to lower N mineralisation. Fortunately, chemical recalcitrance had been measured on samples taken from the field site, which helped to divide the total SON and SOC stocks into inert and slow pools (Springob & Kirchmann 2002; 2010). The uncertainty in the representation of the organic pools has a large impact on simulated N uptake, N leaching and yield. Therefore, more robust ways to represent and calibrate this part of the model would greatly reduce uncertainty. Some soil–vegetation models include descriptions of organic matter turnover that are based on measurable pools (Zhang et al. 2023). This would be especially helpful at field sites like Mellby, which have high amounts of recalcitrant organic matter due to the historical land-use.

7. Conclusions and future perspectives

7.1 Conclusions

The results obtained in this thesis highlight the need for climate change adaptations to meet water quality goals in nitrate vulnerable zones in the Nordic countries. Both analyses of field measurements over a long time-period (1989–2023) and projections into the future with a crop model strongly indicate that N leaching will increase with a warming climate if no mitigation measures are taken. The results show that an under-sown cover crop, perennial ryegrass, is effective in reducing N leaching both under current (measurements) and future climate (projections) even when it is grown and incorporated into the soil year after year.

Results also showed correlations between higher N leaching and years with warmer weather related to variations in the NAOi, which showed a positive trend after 2010 and correlated with temperature and precipitation. N concentrations in drainage water from the treatment without cover crops increased after 2010 and N leaching was positively correlated with NAOi. These two effects were not seen in the treatment with cover crops. In contrast, N uptake by the cover crop correlated positively with NAOi, which confirms that the cover crop was able to efficiently reduce N leaching also in periods with a warmer climate.

The long-term projections of N fluxes in cereal systems with and without cover crops, based on modelling the period from 2020 to 2100, indicated that N leaching from systems with spring cereals without cover crops, will increase in a warming climate even though the soil organic N pool might decrease due to faster decomposition. In the treatment with a cover crop, simulated N leaching remained low even towards the end of the century, and the efficiency of the cover crop in reducing N leaching from the soil system did not seem to decline in any of the climate scenarios. Meanwhile, the soil organic N pool steadily increased, due to the annual incorporation of cover crop biomass into the soil. This larger pool of organic N might lead to higher N leaching if a cover crop is not grown or fails to establish. Moreover, the larger N uptake and biomass in a warmer climate mean that cover crops are potentially more valuable for fodder production or bioenergy purposes.

In the climate projections, the main crop was both sown and harvested earlier, which caused yields to decrease as less radiation was available earlier in the season. This highlights the need for slower-maturing cultivars. At the same time, the earlier harvest increased the time for cover crop growth and N uptake. This raises the question of how best to utilise a longer and hotter growing season under the light conditions prevailing in Nordic countries.

The model calibrations for different treatments (with and without N fertiliser and with and without cover crops) resulted in significantly different values for some of the model parameters (e.g. the decomposition rate constant for soil organic matter). This indicates that different management practices, such as the introduction of N fertiliser or a cover crop might result in changes in the soil microbial communities that require treatment-specific model calibrations. Feedbacks related to different soil and crop management practices are even more complex and difficult to handle in models when the management of the agricultural system changes with time. The choice of calibration strategy might be especially critical when extrapolating results to future climate conditions. Long-term calibrations against observations for contrasting soil and crop management practices might contribute to more robust parameterisations and a better constraint on parameter ranges.

7.2 Future research topics

Optimising crop growth in the future climate

The decline in yield obtained in the projections with climate change (Paper III) raised several questions concerning how the longer vegetation period could be better utilised. Earlier sowing times might require slower maturing cultivars which could benefit from the longer growing season. Exploring optimum sowing times for longer growing seasons will be important at higher latitudes, since solar radiation is a limiting factor early in the season in the Nordic countries. Another, equally important factor is that careful selection of cultivar and sowing date can help minimise the impact of heat and drought stress, both of which are expected to increase in the future climate (Appiah et al. 2023). In addition, it will likely also be possible to grow new cover crop species. Thus, using soil–vegetation models with future climate scenarios to explore the optimal design of both cultivars and new cropping systems would be an interesting area of research. This could also help guide policymaking as well as inform both crop breeders and the design and setup of new field experiments.

Model projections with more realistic crop rotations and management

The continuous cultivation of under-sown ryegrass, every year, is plausible but highly unlikely to be adopted by farmers in practice. Thus, the results for the treatment with cover crops should be considered as an extreme, which is useful as a reference to improve our understanding of the system. However, future research should also focus on using the model to explore more realistic cropping systems under future climate conditions. Applying models outside the range for which they were calibrated will always involve uncertainties in the predictions. This is especially the case since management practices such as N fertilisation and cover crops may affect decomposition rates, as indicated in this study. Nevertheless, it would be very useful to explore the long-term impacts of different management strategies, such as crop rotations, the frequency of cover crop and adaptation of N fertilisation in a future climate, based on modelling and data from other sites and soils.

Model development and calibration strategies for reducing uncertainty

A database with crop-specific parameter values for different species and varieties, linked to CoupModel, would help reduce uncertainties, but would require detailed data on crop phenology and substantial time to develop. Initialisation of the model based on measurable soil organic carbon and nitrogen fractions would also improve the accuracy of the model simulations. Implementation of a function to account for elevated CO_2 concentrations also when using daily climate data as input, might contribute to more realistic simulations of yield response under climate change. Model calibration and testing against experiments that mimic future climate scenarios would add further insights about responses to climate change.

8. References

Ahl, T. & Oden, S. (1975). Eutrofierung. *Nordforks Milovadssekreteriate Publ Uppsala, i*, 99–133

Andersen, M.S., Engedal, T., Bruun, S., Jensen, L.S. & Hansen, V. (2025). Emissions of N2O following field incorporation of leguminous and non-leguminous cover crops. *Agriculture, Ecosystems & Environment*, 379, 109335. https://doi.org/10.1016/j.agee.2024.109335

Andersson, S., Bärring, L., Landelius, T., Samuelsson, P. & Schimanke, S. (2021). *SMHI Gridded Climatology*. (RMK, Rapport Meteorologi och Klimatologi, 03472116 (ISSN)). http://urn.kb.se/resolve?urn=urn:nbn:se:smhi:diva-6192 [2021-11-22]

Aronsson, H., Hansen, E.M., Thomsen, I.K., Liu, J., Ogaard, A.F., Kankanen, H. & Ulen, B. (2016). The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. *Journal of Soil and Water Conservation*, 71 (1), 41–55. https://doi.org/10.2489/jswc.71.1.41

Aronsson, H., Stenberg, M. & Ulén, B. (2011). Leaching of N, P and glyphosate from two soils after herbicide treatment and incorporation of a ryegrass catch crop. *Soil Use and Management*, 27 (1), 54–68. https://doi.org/10.1111/j.1475-2743.2010.00311.x

Aronsson, H. & Torstensson, G. (2009). *Långsiktiga effekter av flytgödsel och fånggrödor på växtnäringsdynamik i marken och utlakning Mellby försöksfält 1989-2009*. Enheten för biogeofysik och vattenvård, Institutionen för mark och miljö, Sveriges lantbruksuniversitet. (Ekohydrologi, 114)

Barrios Latorre, S.A., Aronsson, H., Björnsson, L., Viketoft, M. & Prade, T. (2024). Exploring the benefits of intermediate crops: Is it possible to offset soil organic carbon losses caused by crop residue removal? *Agricultural Systems*, 215, 103873. https://doi.org/10.1016/j.agsy.2024.103873

Bartel, C.A., Archontoulis, S.V., Lenssen, A.W., Moore, K.J., Huber, I.L., Laird, D.A. & Dixon, P.M. (2020). Modeling perennial groundcover effects on annual maize grain crop growth with the Agricultural Production Systems sIMulator. *Agronomy Journal*, 112 (3), 1895–1910. https://doi.org/10.1002/agj2.20108

Berghuijs, H.N.C., Wang, Z., Stomph, T.J., Weih, M., Van der Werf, W. & Vico, G. (2020). Identification of species traits enhancing yield in

wheat-faba bean intercropping: development and sensitivity analysis of a minimalist mixture model. *Plant and Soil*, 455 (1–2), 203–226. https://doi.org/10.1007/s11104-020-04668-0
Berghuijs, H.N.C., Weih, M., van der Werf, W., Karley, A.J., Adam, E., Villegas-Fernández, Á.M., Kiær, L.P., Newton, A.C., Scherber, C., Tavoletti, S. & Vico, G. (2021). Calibrating and testing APSIM for wheat-faba bean pure cultures and intercrops across Europe. *Field Crops Research*, 264, 108088. https://doi.org/10.1016/j.fcr.2021.108088
Blombäck, K., Bieroza, M., Fölster, J., Geranmayeh, P., Johnsson, H., Kyllmar, K., lindsjö, A., Mårtensson, K., Persson, K. & Wesström, I. (2025). *Vattenkvalitet och förluster av kväve och fosfor från jordbruksmark*. (Utvärderingsrapport 2025:14). [2026-01-09]
Blombäck, K., Eckersten, H., Lewan, E. & Aronsson, H. (2003). Simulations of soil carbon and nitrogen dynamics during seven years in a catch crop experiment. *Agricultural Systems*, 76 (1), 95–114. https://doi.org/10.1016/S0308-521X(02)00030-6
Boesch, D.F., Brinsfield, R.B. & Magnien, R.E. (2001). Chesapeake Bay Eutrophication: Scientific Understanding, Ecosystem Restoration, and Challenges for Agriculture. *Journal of Environmental Quality*, 30 (2), 303–320. https://doi.org/10.2134/jeq2001.302303x
Böldt, M., Taube, F., Vogeler, I., Reinsch, T., Kluß, C. & Loges, R. (2021). Evaluating Different Catch Crop Strategies for Closing the Nitrogen Cycle in Cropping Systems—Field Experiments and Modelling. *Sustainability*, 13 (1), 394. https://doi.org/10.3390/su13010394
Brisson, N., Bussière, F., Ozier-Lafontaine, H., Tournebize, R. & Sinoquet, H. (2004). Adaptation of the crop model STICS to intercropping. Theoretical basis and parameterisation. *Agronomie*, 24 (6–7), 409–421. https://doi.org/10.1051/agro:2004031
Brooks, R.H. & Corey, A.T. (1964). *Hydraulic properties of porous media. Hydrology paper No 3.* Colorado State University.
Cameron, K. c., Di, H. j. & Moir, J. l. (2013). Nitrogen losses from the soil/plant system: a review. *Annals of Applied Biology*, 162 (2), 145–173. https://doi.org/10.1111/aab.12014
Chimonyo, V.G.P., Modi, A.T. & Mabhaudhi, T. (2016). Simulating yield and water use of a sorghum–cowpea intercrop using APSIM. *Agricultural Water Management*, 177, 317–328. https://doi.org/10.1016/j.agwat.2016.08.021
Collentine, D. & Johnsson, H. (2013). Evaluating the effect of climate variation on the cost efficiency of a crop permit policy in Southern

Sweden. *Journal of Water and Climate Change*, 4 (2), 110–117. https://doi.org/10.2166/wcc.2013.057

Conrad, Y. & Fohrer, N. (2009). Modelling of nitrogen leaching under a complex winter wheat and red clover crop rotation in a drained agricultural field. *Physics and Chemistry of the Earth, Parts A/B/C*, 34 (8–9), 530–540. https://doi.org/10.1016/j.pce.2008.08.003

Constantin, J., Beaudoin, N., Launay, M., Duval, J. & Mary, B. (2012). Long-term nitrogen dynamics in various catch crop scenarios: Test and simulations with STICS model in a temperate climate. *Agriculture, Ecosystems & Environment*, 147, 36–46. https://doi.org/10.1016/j.agee.2011.06.006

Constantin, J., Le Bas, C. & Justes, E. (2015). Large-scale assessment of optimal emergence and destruction dates for cover crops to reduce nitrate leaching in temperate conditions using the STICS soil–crop model. *European Journal of Agronomy*, 69, 75–87. https://doi.org/10.1016/j.eja.2015.06.002

Constantin, J., Raynal, H., Casellas, E., Hoffmann, H., Bindi, M., Doro, L., Eckersten, H., Gaiser, T., Grosz, B., Haas, E., Kersebaum, K.-C., Klatt, S., Kuhnert, M., Lewan, E., Maharjan, G.R., Moriondo, M., Nendel, C., Roggero, P.P., Specka, X., Trombi, G., Villa, A., Wang, E., Weihermüller, L., Yeluripati, J., Zhao, Z., Ewert, F. & Bergez, J.-E. (2019). Management and spatial resolution effects on yield and water balance at regional scale in crop models. *Agricultural and Forest Meteorology*, 275, 184–195. https://doi.org/10.1016/j.agrformet.2019.05.013

Corbeels, M., Berre, D., Rusinamhodzi, L. & Lopez-Ridaura, S. (2018). Can we use crop modelling for identifying climate change adaptation options? *Agricultural and Forest Meteorology*, 256–257, 46–52. https://doi.org/10.1016/j.agrformet.2018.02.026

CoupModel. 2026. Coupled heat and mass transfer model for the soil-plant-atmosphere system. [online]. https://www.coupmodel.com/ [2026-01-15]

Cyle, K.T., Hill, N., Young, K., Jenkins, T., Hancock, D., Schroeder, P.A. & Thompson, A. (2016). Substrate quality influences organic matter accumulation in the soil silt and clay fraction. *Soil Biology and Biochemistry*, 103, 138–148. https://doi.org/10.1016/j.soilbio.2016.08.014

Davies, D.B., Garwood, T.W.D. & Rochford, A.D.H. (1996). Factors affecting nitrate leaching from a calcareous loam in East Anglia. *The Journal of Agricultural Science*, 126 (1), 75–86. https://doi.org/10.1017/S0021859600088821

Delwiche, C.C. (1970). The Nitrogen Cycle. *Scientific American*, 223 (3), 136–147

Doltra, J., Lægdsmand, M. & Olesen, J.E. (2014). Impacts of projected climate change on productivity and nitrogen leaching of crop rotations in arable and pig farming systems in Denmark. *The Journal of Agricultural Science*, 152 (1), 75–92. https://doi.org/10.1017/S0021859612000846

Eriksson, J., Mattsson, L. & Söderström, M. (2010). *Tillståndet i svensk åkermark och gröda Data från 2001-2007 rapport 6349*.

Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z. & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience*, 1 (10), 636–639. https://doi.org/10.1038/ngeo325

Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J. & Taylor, K.E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9 (5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Gaudio, N., Ripoche, D., Launay, M., Tribouillois, H. & Justes, E. (2016). Evaluation of the STICS soil-crop model for modelling arable intercrops. *Proceedings of International Crop Modelling Symposium*, 2016. 2

Hansen, E.M. & Djurhuus, J. (1997). Nitrate leaching as influenced by soil tillage and catch crop. *Soil and Tillage Research*, 41 (3), 203–219. https://doi.org/10.1016/S0167-1987(96)01097-5

He, H., Jansson, P.-E. & Gärdenäs, A.I. (2021). CoupModel (v6.0): an ecosystem model for coupled phosphorus, nitrogen, and carbon dynamics – evaluated against empirical data from a climatic and fertility gradient in Sweden. *Geoscientific Model Development*, 14 (2), 735–761. https://doi.org/10.5194/gmd-14-735-2021

Hellsten, S., Dalgaard, T., Rankinen, K. & Tørseth, K. (2017). *Nordic nitrogen and agriculture*. Nordic Council of Ministers. https://doi.org/10.6027/TN2017-547

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R. & Rozum, I. (2018). ERA5 hourly data on single levels from 1979 to present, Copernicus Climate Change Service (C3S) Climate Data Store (CDS)[data set].

Hooghoudt, S. (1940). Contributions to knowledge of some natural properties of soil. VII. General consideration of the problem of local draining of soil, and of infiltration from parallel running drains and open drain furrows, ditches and drainage channels. *Verslagen van Landbouwkundige Onderzoekingen*, 515–707

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B. & Yiou, P. (2014). EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, 14 (2), 563–578. https://doi.org/10.1007/s10113-013-0499-2

Jansson, P. & Karlberg, L. (2004). COUP manual: Coupled heat and mass transfer model for soil-plant-atmosphere systems. *Technical manual for the CoupModel*, 1–453

Jarvis, S., Hutchings, N., Brentrup, F., Olesen, J.E. & van de Hoek, K.W. (2011). Nitrogen flows in farming systems across Europe. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., & Grizzetti, B. (eds) *The European Nitrogen Assessment*. Cambridge University Press. 211–228. https://doi.org/10.1017/CBO9780511976988.013

Johnsson, H. (1991). The soil at Mellby experimental field. *Internal Report. Div of Water Management, Swedish University of Agricultural Sciences. Uppsala*,

Johnsson, H., Mårtensson, K., Lindsjö, A., Persson, K., Andrist Rangel, Y. & Blombäck, K. (2024). Läckage av näringsämnen från svensk åkermark 1995-2019. *Ekohydrologi*, (185)

Karlsson-Strese, E.-M., Umaerus, M. & Rydberg, I. (1996). Strategy for Catch Crop Development: I. Hypothetical Ideotype and Screening of Species. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science*, 46 (2), 106–111. https://doi.org/10.1080/09064719609413122

Kjær, S.T., Lang, R., Kätterer, T. & Dörsch, P. (2026). Species specific effects of cover crops on nitrous oxide emissions in hemiboreal cereal production: The importance of freeze-thaw driven emissions. *Agriculture, Ecosystems & Environment*, 397, 110061. https://doi.org/10.1016/j.agee.2025.110061

Kjellström, E., Thejll, P., Rummukainen, M., Christensen, J., Boberg, F., Christensen, O. & Fox Maule, C. (2013). Emerging regional climate change signals for Europe under varying large-scale circulation conditions. *Climate Research*, 56 (2), 103–119. https://doi.org/10.3354/cr01146

Knörzer, H., Lawes, R., Robertson, M., Graeff-Hönninger, S. & Claupein, W. (2011). Evaluation and performance of the APSIM crop growth model for German winter wheat, maize and fieldpea varieties in monocropping and intercropping systems. *Journal of Agricultural Science and Technology*, 9, 698–717

Labaz, B., Hartemink, A.E., Zhang, Y., Stevenson, A. & Kabała, C. (2024). Organic carbon in Mollisols of the world − A review. *Geoderma*, 447, 116937. https://doi.org/10.1016/j.geoderma.2024.116937

Lagerquist, E., Vogeler, I., Kumar, U., Bergkvist, G., Lana, M., Watson, C.A. & Parsons, D. (2024). Assessing the effect of intercropped leguminous service crops on main crops and soil processes using APSIM NG. *Agricultural Systems*, 216, 103884. https://doi.org/10.1016/j.agsy.2024.103884

Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science*, 304 (5677), 1623–1627. https://doi.org/10.1126/science.1097396

Laurila, H. (2001). Simulation of spring wheat responses to elevated CO2 and temperature by using CERES-wheat crop model. *Agricultural and Food Science*, 10 (3), 175–196. https://doi.org/10.23986/afsci.5692

Lavallee, J.M., Soong, J.L. & Cotrufo, M.F. (2020). Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology*, 26 (1), 261–273. https://doi.org/10.1111/gcb.14859

Lewan, E. (1993). Evaporation and discharge from arable land with cropped or bare soils during winter. Measurements and simulations. *Agricultural and Forest Meteorology*, 64 (3–4), 131–159. https://doi.org/10.1016/0168-1923(93)90026-E

Lewan, E. (1994). Effects of a catch crop on leaching of nitrogen from a sandy soil: Simulations and measurements. *Plant and Soil*, 166 (1), 137–152. https://doi.org/10.1007/BF02185490

Manevski, K., Børgesen, C.D., Andersen, M.N. & Kristensen, I.S. (2015). Reduced nitrogen leaching by intercropping maize with red fescue on sandy soils in North Europe: a combined field and modeling study. *Plant and Soil*, 388 (1–2), 67–85. https://doi.org/10.1007/s11104-014-2311-6

Meisinger, J., Hargrove, W., Mikkelsen, R., Williams, J. & Benson, V. (1991). Effects of cover crops on groundwater quality. *Cover crops for clean water*, 57–68

Meurer, K.H.E., Chenu, C., Coucheney, E., Herrmann, A.M., Keller, T., Kätterer, T., Nimblad Svensson, D. & Jarvis, N. (2020). Modelling dynamic interactions between soil structure and the storage and turnover of soil organic matter. *Biogeosciences Discussions*, 1–34

Meyer, N., Bergez, J.-E., Constantin, J. & Justes, E. (2019). Cover crops reduce water drainage in temperate climates: A meta-analysis. *Agronomy for Sustainable Development*, 39 (1), 3. https://doi.org/10.1007/s13593-018-0546-y

Minoli, S., Jägermeyr, J., Asseng, S., Urfels, A. & Müller, C. (2022). Global crop yields can be lifted by timely adaptation of growing periods to climate change. *Nature Communications*, 13, 7079. https://doi.org/10.1038/s41467-022-34411-5

Monteith, J. (1965). L.(1965). Evaporation and environment. *Proceedings of Fogg, GE (éd) The State and Movement of LYater in Living Organisms, 19th Symp. Soc. Exp. Biol. Cambridge University Press, Cambridge*, 1965. 205–234

Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, 12 (3), 513–522. https://doi.org/10.1029/WR012i003p00513

Müller, T., Thorup-Kristensen, K., Magid, J., Jensen, L.S. & Hansen, S. (2006). Catch crops affect nitrogen dynamics in organic farming systems without livestock husbandry—Simulations with the DAISY model. *Ecological Modelling*, 191 (3–4), 538–544. https://doi.org/10.1016/j.ecolmodel.2005.05.026

Norberg, L. & Aronsson, H. (2024). Effects of spring and autumn tillage, catch crops, and pig manure application on long-term nutrient leaching from a loamy sand. *European Journal of Agronomy*, 156, 127156. https://doi.org/10.1016/j.eja.2024.127156

P-E. Jansson (2012). CoupModel: Model Use, Calibration, and Validation. *Transactions of the ASABE*, 55 (4), 1337–1346. https://doi.org/10.13031/2013.42245

Peltre, C., Nielsen, M., Christensen, B.T., Hansen, E.M., Thomsen, I.K. & Bruun, S. (2016). Straw export in continuous winter wheat and the ability of oil radish catch crops and early sowing of wheat to offset soil C and N losses: A simulation study. *Agricultural Systems*, 143, 195–202. https://doi.org/10.1016/j.agsy.2016.01.002

Poeplau, C., Aronsson, H., Myrbeck, Å. & Kätterer, T. (2015). Effect of perennial ryegrass cover crop on soil organic carbon stocks in

southern Sweden. *Geoderma Regional*, 4, 126–133. https://doi.org/10.1016/j.geodrs.2015.01.004
Quemada, M., Lassaletta, L., Leip, A., Jones, A. & Lugato, E. (2020). Integrated management for sustainable cropping systems: Looking beyond the greenhouse balance at the field scale. *Global Change Biology*, 26 (4), 2584–2598. https://doi.org/10.1111/gcb.14989
Rashid, M.A., Bruun, S., Styczen, M.E., Ørum, J.E., Borgen, S.K., Thomsen, I.K. & Jensen, L.S. (2021). Scenario analysis using the Daisy model to assess and mitigate nitrate leaching from complex agro-environmental settings in Denmark. *Science of The Total Environment*, 151518. https://doi.org/10.1016/j.scitotenv.2021.151518
Rezaei, E.E., Webber, H., Asseng, S., Boote, K., Durand, J.L., Ewert, F., Martre, P. & MacCarthy, D.S. (2023). Climate change impacts on crop yields. *Nature Reviews Earth & Environment*, 4 (12), 831–846. https://doi.org/10.1038/s43017-023-00491-0
Salo, T.J., Palosuo, T., Kersebaum, K.C., Nendel, C., Angulo, C., Ewert, F., Bindi, M., Calanca, P., Klein, T., Moriondo, M., Ferrise, R., Olesen, J.E., Patil, R.H., Ruget, F., Takáč, J., Hlavinka, P., Trnka, M. & Rötter, R.P. (2016). Comparing the performance of 11 crop simulation models in predicting yield response to nitrogen fertilization. *The Journal of Agricultural Science*, 154 (7), 1218–1240. https://doi.org/10.1017/S0021859615001124
Schwartzkopff, M.V., Miranda-Vélez, J.F., Abrahamsen, P., Grønning, C.R. & Jensen, L.S. (2025). Daisy model calibration for simulating nitrogen leaching in cereals with catch crops. *Nutrient Cycling in Agroecosystems*, 132 (1), 8. https://doi.org/10.1007/s10705-025-10459-9
Shili-Touzi, I., De Tourdonnet, S., Launay, M. & Doré, T. (2010). Does intercropping winter wheat (Triticum aestivum) with red fescue (Festuca rubra) as a cover crop improve agronomic and environmental performance? A modeling approach. *Field Crops Research*, 116 (3), 218–229
Six, J., Conant, R.T., Paul, E.A. & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, 241 (2), 155–176. https://doi.org/10.1023/A:1016125726789
Spohn, M., Pötsch, E.M., Eichorst, S.A., Woebken, D., Wanek, W. & Richter, A. (2016). Soil microbial carbon use efficiency and biomass turnover in a long-term fertilization experiment in a temperate

grassland. *Soil Biology and Biochemistry*, 97, 168–175. https://doi.org/10.1016/j.soilbio.2016.03.008
Springob, G. & Kirchmann, H. (2002). C-rich sandy Ap horizons of specific historical land-use contain large fractions of refractory organic matter. *Soil Biology and Biochemistry*, 34 (11), 1571–1581. https://doi.org/10.1016/S0038-0717(02)00127-X
Springob, G. & Kirchmann, H. (2010). Ratios of carbon to nitrogen quantify non-texture-stabilized organic carbon in sandy soils. *Journal of Plant Nutrition and Soil Science*, 173 (1), 16–18. https://doi.org/10.1002/jpln.200900289
Strandberg, G., Thomasson, A., Bärring, L., Kjellström, E., Sahlin, M., Wilcke, R. & Nikulin, G. (2025). Projected climate change in Fennoscandia – and its relation to ensemble spread and global trends. Other aspects of weather and climate dynamics. https://doi.org/10.5194/egusphere-2025-2002
Sveriges meteorologiska och hydrologiska institut (SMHI). 2025. Griddad nederbörd- och temperaturdata (PTHBV) [online]. https://www.smhi.se/data/nederbord-och-fuktighet/nederbord/griddad-nederbord--och-temperaturdata [2024-12-10]
Teixeira, E., Kersebaum, K.C., Ausseil, A.-G., Cichota, R., Guo, J., Johnstone, P., George, M., Liu, J., Malcolm, B., Khaembah, E., Meiyalaghan, S., Richards, K., Zyskowski, R., Michel, A., Sood, A., Tait, A. & Ewert, F. (2021). Understanding spatial and temporal variability of N leaching reduction by winter cover crops under climate change. *Science of The Total Environment*, 771, 144770. https://doi.org/10.1016/j.scitotenv.2020.144770
Thomsen, I. k., Djurhuus, J. & Christensen, B. t. (2003). Long continued applications of N fertilizer to cereals on sandy loam: grain and straw response to residual N. *Soil Use and Management*, 19 (1), 57–64. https://doi.org/10.1111/j.1475-2743.2003.tb00280.x
Thomsen, I.K. & Hansen, E.M. (2014). Cover crop growth and impact on N leaching as affected by pre- and postharvest sowing and time of incorporation. *Soil Use and Management*, 30 (1), 48–57. https://doi.org/10.1111/sum.12083
Thomsen, I.K., Lægdsmand, M. & Olesen, J.E. (2010). Crop growth and nitrogen turnover under increased temperatures and low autumn and winter light intensity. *Agriculture, Ecosystems & Environment*, 139 (1–2), 187–194. https://doi.org/10.1016/j.agee.2010.07.019
Thorsøe, M.H., Andersen, M.S., Brady, M.V., Graversgaard, M., Kilis, E., Pedersen, A.B., Pitzén, S. & Valve, H. (2022). Promise and

performance of agricultural nutrient management policy: Lessons from the Baltic Sea. *Ambio*, 51 (1), 36–50. https://doi.org/10.1007/s13280-021-01549-3

Thorup-Kristensen, K. (1993). The effect of nitrogen catch crops on the nitrogen nutrition of a succeeding crop: I. Effects through mineralization and pre-emptive competition. *Acta Agriculturae Scandinavica B-Plant Soil Sciences*, 43 (2), 74–81

Thorup-Kristensen, K. & Dresbøll, D.B. (2010). Incorporation time of nitrogen catch crops influences the N effect for the succeeding crop: N effect of catch crop incorporation time. *Soil Use and Management*, 26 (1), 27–35. https://doi.org/10.1111/j.1475-2743.2009.00255.x

Thorup-Kristensen, K., Magid, J. & Jensen, L.S. (2003). Catch crops and green manures as biological tools in nitrogen management in temperate zones. In: *Advances in Agronomy*. Elsevier. 227–302. https://doi.org/10.1016/S0065-2113(02)79005-6

Tonitto, C., David, M.B. & Drinkwater, L.E. (2006). Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. *Agriculture, Ecosystems & Environment*, 112 (1), 58–72. https://doi.org/10.1016/j.agee.2005.07.003

Tootoonchi, F., Bergkvist, G. & Vico, G. (2025). Warmer growing seasons improve cereal yields in Northern Europe only with increasing precipitation. *EGUsphere*, 1–30. https://doi.org/10.5194/egusphere-2025-1982

Torstensson, G. (1998). Nitrogen Delivery and Utilization by Subsequent Crops after Incorporation of Leys with Different Plant Composition. *Biological Agriculture & Horticulture*, 16 (2), 129–143. https://doi.org/10.1080/01448765.1998.9755228

Tribouillois, H., Constantin, J. & Justes, E. (2018). Cover crops mitigate direct greenhouse gases balance but reduce drainage under climate change scenarios in temperate climate with dry summers. *Global Change Biology*, 24 (6), 2513–2529. https://doi.org/10.1111/gcb.14091

Van Schöll, L., Van Dam, A. & Leffelaar, P. (1997). Mineralisation of nitrogen from an incorporated catch crop at low temperatures: experiment and simulation. *Plant and Soil*, 188 (2), 211–219

Wallgren, B. & Lindén, B. (1994). Effects of catch crops and ploughing times on soil mineral nitrogen. *Swedish Journal of Agricultural Research (Sweden)*,

Wang, B., Jägermeyr, J., O'Leary, G.J., Wallach, D., Ruane, A.C., Feng, P., Li, L., Liu, D.L., Waters, C., Yu, Q., Asseng, S. & Rosenzweig, C.

(2024). Pathways to identify and reduce uncertainties in agricultural climate impact assessments. *Nature Food*, 5 (7), 550–556. https://doi.org/10.1038/s43016-024-01014-w

Willaume, M., Raynal, H., Bergez, J.-E. & Constantin, J. (2025). Optimization of nitrogen management and greenhouse gas balance in agroecological cropping systems in a climate change context. *Agricultural Systems*, 222, 104182. https://doi.org/10.1016/j.agsy.2024.104182

Yin, X., Beaudoin, N., Ferchaud, F., Mary, B., Strullu, L., Chlébowski, F., Clivot, H., Herre, C., Duval, J. & Louarn, G. (2020). Long-term modelling of soil N mineralization and N fate using STICS in a 34-year crop rotation experiment. *Geoderma*, 357, 113956. https://doi.org/10.1016/j.geoderma.2019.113956

Yu, J., Rezaei, E.E., Thompson, J.B., Reckling, M. & Nendel, C. (2024). Modelling crop yield in a wheat–soybean relay intercropping system: A simple routine in capturing competition for light. *European Journal of Agronomy*, 153, 127067. https://doi.org/10.1016/j.eja.2023.127067

Zhang, Y., King, A.E., Hamilton, E. & Cotrufo, M.F. (2023). Representing cropping systems with the MEMS 2.0 ecosystem model. agriRxiv. https://doi.org/10.31220/agriRxiv.2023.00206

Popular science summary

It has been known since the 1970's that the use of nitrogen fertiliser on agricultural fields may cause environmental problems, especially the eutrophication of lakes and seas. Much work has since been done to find ways to reduce nitrogen leaching from arable land whilst maintaining yields. In the Nordic countries, the most effective method is to grow so-called cover crops that can take up excess nitrogen after the harvest of the main crop. A substantial amount of the nitrogen that is lost through leaching comes from the microbial decomposition of soil organic matter which transforms organic nitrogen into mineral nitrogen (a process called mineralisation). Some cover crops, such as ryegrass, can be sown together with the main crop. The main crop suppresses the growth of the cover crop until it has been harvested. The cover crop then grows freely without competition and takes up nitrogen that would otherwise have been lost through leaching. This is especially effective in the Nordic countries, which have short growing seasons and therefore little time for farmers to establish a new crop.

Climate change is already affecting agricultural ecosystems in the Nordic countries and is expected to have stronger impacts in the future. Increased nitrogen mineralisation due to higher temperatures, together with increased winter precipitation, is likely to result in greater nitrogen leaching, particularly under bare-soil conditions. Therefore, it is important to explore and estimate the impact of cover crops, such as under-sown ryegrass, both in current and future climate conditions. In this thesis, the impacts of perennial ryegrass cover crops on nitrogen flows and crop yields were studied both under current and future climate conditions. The work was based on data from an ongoing long-term field experiment in Mellby, south-west Sweden, which started in 1983. The data was analysed statistically and also used to support simulations with a soil-vegetation model (CoupModel).

The model was calibrated using field data from treatments with and without an under-sown cover crop. It was then used to explore how these systems might respond under future climate conditions (2020–2100) using three representative concentration pathways (RCPs), representing low, medium, and high greenhouse gas emission scenarios, based on climate data from five regionally downscaled climate models. The field observations showed that the cover crops reduced nitrogen leaching in the period 1989–2023, without any decline in their effectiveness in reducing nitrogen losses.

Nitrogen leaching in the treatment without cover crops was more sensitive to temperature and the North Atlantic Oscillation index. Higher values of this index are associated with milder winters, and N uptake by the cover crop was positively correlated with this index. This indicates that perennial ryegrass can take up more nitrogen in years with a risk for high nitrogen leaching. Model projections suggested that N mineralisation will increase until the end of the century due to higher temperatures and repeated incorporation of cover crop biomass. While nitrogen leaching may also increase slightly when a cover crop is grown, long-term simulations indicate that the increase is substantially larger in systems without cover crops. Increasing temperatures led to earlier sowing and to earlier harvests. This gave the cover crop more time to grow and increased its annual N uptake. The earlier sowing led to yield losses in a future climate since more of the crop growth occurred in early spring when radiation was limiting. In the current climate, yields were not statistically different between treatments with and without a cover crop. The simulated soil organic nitrogen increased with time when a cover crop was grown and incorporated annually, whereas it decreased in the treatment without cover crops.

In conclusion, the results in this thesis highlight the flexibility and potential of under-sown ryegrass to reduce nitrogen leaching in mild and wet years both under current and future climate conditions. The findings also underscore the importance of maintaining and further adapting cover crop-based systems under future climates to mitigate increasing nitrogen leaching risks. Such adaptation may include optimising crop and cultivar selection to take advantage of longer growing seasons. Future research on cover crop systems in the Nordic countries should therefore focus on the long-term effects of alternative cover crop species, more slowly maturing main-crop cultivars, and novel crop rotations, with the aim of maximising the duration of soil cover.

Populärvetenskaplig sammanfattning

Sedan 1970-talet är det känt att jordbruket och dess användning av kvävegödsel kan orsaka miljöproblem, särskilt övergödning av sjöar och hav. Sedan dess har mycket arbete lagts ned på att hitta sätt att minska kväveläckaget från åkermark utan att minska skörden. I de nordiska länderna är en av de mest effektiva metoderna att odla så kallade mellangrödor som kan ta upp överskott av kväve efter skörden av huvudgrödan. Mellangrödan kan också ta upp kväve som frigörs vid mikrobiell nedbrytning av organiskt material i marken, när organiskt kväve omvandlas till mineraliskt kväve (en process som kallas mineralisering). Vissa mellangrödor såsom rajgräs kan sås tillsammans med huvudgrödan. Mellangrödans tillväxt hämmas tills dess att huvudgrödan skördats. Därefter växer mellangrödan fritt utan konkurrens och tar upp kväve som annars skulle ha gått förlorat och transporterats med dräneringsvattnet till grund- och ytvatten. Att odla mellangrödor är särskilt effektivt på nordiska breddgrader där klimatet medför korta växtsäsonger och marken ofta ligger obevuxen under höst och vinter efter skörd av ettåriga huvudgrödor.

Klimatförändringar påverkar redan idag jordbruket i de nordiska länderna och förväntas få ännu större effekter i framtiden. Ökad kvävemineralisering på grund av högre temperaturer, tillsammans med ökad vinternederbörd, kommer sannolikt att leda till större kväveläckage, särskilt om ingen gröda täcker marken under höst och vinter när avrinningen från marken är hög. Därför är det viktigt att undersöka och kvantifiera effekterna av mellangrödor, såsom insått rajgräs, både under nuvarande och framtida klimatförhållanden. I denna avhandling studerades effekterna av klimatet på kvävedynamik, kväveutlakning och skörd i odlingssystem med och utan årlig insådd av rajgräs, dels under de gångna 34 åren (1989–2023), dels under kommande decennier (2020–2100). Arbetet baserades på modellsimuleringar med en mark-växtmodell (CoupModel), statistisk analys av data från ett pågående långliggande fältförsök i sydvästra Sverige (Mellby, startat 1983), samt klimatscenarier från SMHI/EURO-CORDEX.

Modellen kalibrerades mot observationer av kväveutlakning, skörd och biomassa från fältförsökets behandlingar med och utan insådd mellangröda. Därefter användes modellen för att simulera kvävevariabler i dessa system under framtida klimatförhållanden (2020–2100) med drivdata från klimatscenarier. För att beakta osäkerheten i framtida klimat kördes modellen med flera olika drivdataserier, vilka representerade fem olika klimatmodeller och tre olika utsläppsscenarier (låga, medelhöga och höga utsläpp av växthusgaser). Statistisk analys av data från fältexperimentet visade att mellangrödorna minskade kväveläckaget under 1989–2023, med bibehållen effekt under hela perioden, trots årlig tillförsel av kväve via nedplöjning av mellangrödans biomassa på våren före nästa sådd. Kväveläckaget i ledet utan mellangrödor ökade däremot över tid och var mer känsligt för temperaturen och variationer i klimatet, som här representerades av årliga värden på Nordatlantiska oscillationsindexet (NAOi). Högre värden på NAOi är förknippade med mildare vintrar. Mellangrödans kväveupptag var positivt korrelerat med NAOi, vilket indikerar att rajgräs kan ta upp mer kväve under år med risk för stort kväveläckage. Det fanns ingen statistisk skillnad i skörd mellan leden med och utan mellangröda under perioden av observationer. Modellsimuleringar med drivdata från klimatscenarierna tyder på att kvävemineraliseringen i system med årlig insådd mellangröda ökar under den simulerade perioden fram till slutet av seklet, till följd av högre temperaturer och årlig nedplöjning av mellangrödans biomassa. Trots detta visar de långsiktiga simuleringarna att kväveutlakningen endast ökar marginellt eller inte alls i system med insådd mellangröda, även om den odlas och brukas ner varje år under flera decennier fram till seklets slut. Simulerat kväveläckage för ledet utan mellangröda ökade under samma period i betydligt högre takt. Stigande temperaturer ledde, i simuleringarna med förändrat klimat, till successivt tidigare sådd och tidigare skörd av huvudgrödan. Detta gav mellangrödan mer tid att växa under gynnsammare temperaturer, vilket ökade dess årliga kväveupptag. Tidigare sådd resulterade även i sjunkande skördenivå av huvudgrödan i båda led, eftersom en större del av huvudgrödans tillväxt skedde tidigt på våren när solinstrålningen var begränsad. I ledet utan mellangröda minskade mängden organiskt kväve i marken, på grund av ökad nedbrytning i varmare klimat. Däremot ökade mängden organiskt kväve i marken successivt i ledet med mellangröda även under varmare klimat. Den årliga tillförseln av kväve via mellangrödans nedplöjda biomassa överskuggade alltså ökningen i nedbrytning till följd av ökad temperatur.

Sammanfattningsvis visar resultaten i denna avhandling på flexibiliteten och potentialen hos insått rajgräs för att minska kväveläckage under milda och regniga år, både under nuvarande och framtida klimatförhållanden. Resultaten understryker också vikten av att upprätthålla och ytterligare anpassa system baserade på mellangrödor under framtida klimatförhållanden för att dämpa riskerna för ökat kväveläckage. En sådan anpassning kan innefatta optimering av valet av grödor och sorter för att dra nytta av längre växtsäsonger. Framtida forskning om odlingssystem med mellangrödor i de nordiska länderna bör därför fokusera på de långsiktiga effekterna av olika arter, huvudgrödor med långsammare mognadshastighet och nya växtföljder, med målet att maximera tiden som marken är bevuxen. Med rätt anpassning kan mellangrödor potentiellt även minska behovet av kvävegödsling.

Acknowledgements

I would like to express my sincere gratitude to my main supervisor, Elisabet Lewan, for your continuous support and encouragement throughout these years.

I am also very grateful to my co-supervisor, Helena Aronsson, for your support and for always cheering me on when I struggled. My thanks also go to my external co-supervisors, Erik Kjellström and Stefano Manzoni, for their valuable input and constructive feedback on my work. I am grateful for your comments, suggestions, and discussions. I would like to thank Lisbet Norberg for her collaboration on Paper II.

My warmest thanks go to Per-Erik Jansson for all the help and support you have provided over the years with the modelling aspects of my work. Thank you as well for welcoming me into your fantastic house and garden, and for always being willing to help and discuss ideas.

This PhD-project was funded by FORMAS [project No. 2019–00518] which is gratefully acknowledged.

Special thanks to Nicholas Jarvis, who has helped me immensely over the years with modelling advice and by carefully reading all my manuscripts, including this thesis. Thank you also for organising so many enjoyable meetings and events, both work-related and social. I would also like to thank all my current and former colleagues in the Soil and Environmental Physics group (BGF). Had it not been for John Koestel, Jumpei Fukumasu, and Tobias Klöffel, I am not sure I would have ended up as a PhD student at all.

I also wish to thank all the wonderful people at the Department of Soil and Environment, including fellow PhD students, postdocs, and senior researchers, with whom I have had the privilege to share a workplace. Thank you for many interesting conversations and plenty of laughter along the way.

Finally, I would like to thank my entire family, my friends, and especially my partner Emelie and our daughter Iris, for enriching my life every day.

I

Field Crops Research 326 (2025) 109856

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Insights gained from modeling grain yield, nitrate leaching, and soil nitrogen dynamics in a long-term field experiment with spring cereals on fertilized and unfertilized soil over 35 years

David Nimblad Svensson [a,*], Helena Aronsson [a], Per-Erik Jansson [b], Elisabet Lewan [a]

[a] Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala, Sweden
[b] Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Stockholm, Sweden

ARTICLE INFO

Keywords:
N-mineralization
Trend analysis
Soil organic C
Soil organic N
CoupModel

ABSTRACT

Crop models are useful tools for predicting changes in yield and nitrogen losses in response to changes in agricultural management practices and climate. We used a soil-crop model (CoupModel) to interpret trends in yields, drainage, and nitrate leaching observed for two contrasting treatments (fertilized and unfertilized cereals) in a long-term field experiment (35 years) on a sandy loam in southern Sweden. The model was calibrated using a Monte Carlo-based method, in which the 30 best simulations of 10,000 model runs were identified based on multiple criteria. The posterior distributions differed significantly between the two treatments for 6 of the 16 parameters included. For example, the decomposition rate coefficient of the slow organic matter pool was significantly larger in the unfertilized treatment. The model simulated yearly drainage and nitrate leaching well overall, but did not fully capture between-year variations. Although the simulated mean annual nitrate leaching was 1.4 times greater in the fertilized treatment, N leached per unit of N harvest was twice as large in the unfertilized plot. The model simulated substantial decreases in yield for both treatments in 2018 in response to an extremely hot and dry summer, although not as large as that observed. The range in simulated annual N mineralization due to parameter uncertainty was wider in the fertilized treatment. We conclude that model calibration strategies require careful attention to how different management practices may influence decomposition and long-term N balance components in agroecosystems and that more data on especially belowground biomass would help in reducing uncertainties.

1. Introduction

Indigenous stores of soil nitrogen provide an important resource for N uptake in crops through nitrogen mineralization, in addition to the N applied with fertilizers (Cassman et al., 2002). Nitrogen released by mineralization of organic matter often amounts to more than half of the recovered N in well-fertilized crops (Thomsen et al., 2003). Maintaining soil fertility and a high indigenous N supply is therefore an important management strategy to reduce the need for N fertilizer. Lower input of mineral N provides several benefits, including less addition of reactive N to the ecosystem, which potentially reduces both water and air pollution (Galloway et al., 2003) and provides economic savings for the farmer. However, high mineralization rates in the soil, especially during periods with bare soil, constitute a risk of mineral N accumulation in the soil, which may result in leaching of nitrate (Stenberg et al., 1999) and gaseous losses through denitrification (Mosier et al., 1998). Maintaining and optimizing indigenous soil N supply to the crop as well as reducing the risk of N-losses by management requires an understanding of the system and the long-term storage and change in soil C and N pools.

The mineralization of organic N and immobilization of mineral N are highly dynamic processes that are difficult to measure in the field (Nykänen et al., 2009). Yin et al. (2020) identified four principal ways to estimate N mineralization including (i) laboratory incubation, (ii) using ^{15}N-labeled residues, (iii) in situ N balance methods, and (iv) model simulations. The results of laboratory incubations and isotopic tracer experiments are dependent on experimental conditions. Therefore, models calibrated using such experiments may be poor predictors of N mineralization in field conditions (Cabrera and Kissel, 1988; Johnson et al., 1999). In situ N balance methods such as the 'N-difference' method calculate the difference in N uptake between a crop receiving N

* Corresponding author.
E-mail address: david.nimblad.svensson@slu.se (D. Nimblad Svensson).

https://doi.org/10.1016/j.fcr.2025.109856
Received 12 November 2024; Received in revised form 5 March 2025; Accepted 10 March 2025
Available online 24 March 2025

fertilizer with one that does not. The addition of N may alter the plant's ability to take up N or water, which therefore introduces confounding factors (Cassman et al., 2002). Model simulations may be useful if they correctly capture all components of the N balance (Yin et al., 2020a). Soil-crop models can be used to describe nitrogen dynamics in relation to weather, soil characteristics, crop growth, and management (Kersebaum et al., 2007). Consequently, the long-term effects on soil organic N pools following different fertilization regimes or other management practices can be explored. The knowledge gained by such model applications can be used to assess N leaching risks and mineralization in the short- or long-term for different types of crop and soil management systems.

Agroecosystems include numerous processes and soil-plant interactions. Therefore, soil-crop models are often highly complex with a large number of equations and parameters, which leads to structural and parameter uncertainty. These sources of uncertainty along with uncertainties in the model input data (e.g. weather data, soil data, and data related to observations of crops) lead to uncertainty in model predictions. Furthermore, when a model is run continuously for many years, it must be able to account for carry-over effects between years (Beaudoin et al., 2008). Therefore, long-time series of data are important to evaluate the stability of the model performance over time.

Soil-crop models are seldom universal enough to be directly applied to situations beyond the types of systems and climates for which they were developed and tested. Therefore, crop models generally require some kind of calibration to be useful (Timsina and Humphreys, 2006; Wallach, 2011). It is noteworthy that this is often done by trial and error despite a range of more objective options (Seidel et al., 2018). Moreover, the goal of calibrating crop models has primarily been to find a single acceptable value for each parameter (Alderman and Stanfill, 2017). This approach is problematic, as it neglects the fact that several parameter sets can give equally good fits to the data, a phenomenon referred to as equifinality (Beven, 1993). Following Bayesian theory, a suite of parameter distributions can be used to produce a distribution of outputs instead. In this way, uncertainties in the parameter values are considered (Alderman and Stanfill, 2017). The Generalized Likelihood Uncertainty Estimate method (GLUE) (Beven and Binley, 1992) is an alternative to formal Bayesian methods. It does not rely on statistical assumptions that may not be fulfilled by soil-crop models. Monte Carlo simulation is used to vary the parameters within their "prior" ranges. Then, one or several performance indicators are used to select acceptable parameter sets. A concern with this method is that the choice of performance criteria and the method of combining different criteria introduces subjectivity that influences the results (He et al., 2010). It should be noted that models themselves are to some extent subjective as they are based on a combination of equations, which the developers have chosen to use, not all of which are firmly grounded in proven theory.

CoupModel (Jansson and Karlberg, 2004) is a highly flexible model for soil and vegetation, which was initially especially developed for soil-vegetation ecosystems and prevailing climates in Sweden and Nordic countries. CoupModel takes into account processes related to snow, freezing and thawing, and tile drainage. The latter is estimated to be installed in 49 % of Swedish agricultural land (SCB, 2014). CoupModel and its predecessors (SOIL and SOILN) have been used to study N dynamics in both Sweden and Finland (Aronsson and Torstensson, 1998; Blombäck et al., 2003; Lewan, 1994, 1993; Nykänen et al., 2009; Nylinder et al., 2011; Torstensson and Aronsson, 2000) as well as many contrasting agroecosystems in other climates (e.g. Karlberg et al., 2006; Wu et al., 2019). CoupModel was also applied to study input data resolution effects on crop production in Germany (Constantin et al., 2019; Coucheney et al., 2018; Hoffmann et al., 2015) and recently, to predict future potential yield losses and nitrate leaching for winter wheat (Villa et al., 2022). However, until now the model has only been parameterized and evaluated on field experiments covering limited periods (4–7 years). Long-term predictions and especially climate change impact assessments would benefit from a careful evaluation of soil-vegetation models over periods of at least 20–30 years of field observations related to water and nitrogen flows (Constantin et al., 2012; Yin et al., 2020a). This will help to constrain the model and its parameters, reducing the uncertainty in the predictions and also capturing between-year variations as well as both short-term and long-term feedback under a range of weather conditions.

The aim of this study was to test and evaluate the robustness of a frequently used soil-crop model, CoupModel, from a long-term perspective with a focus on its ability to reproduce harvest, water, and N dynamics in agroecosystems over several decades, based on data and field observations covering 35 years. In particular, we explored between-year variations and potential trends in observed and simulated yields and nitrate leaching. We used the model to simulate and compare the long-term temporal dynamics in nitrogen pools and mineralization in two contrasting treatments, fertilized and unfertilized spring cereals on a sandy loam soil in southern Sweden. Each treatment was calibrated separately to compare potential differences between the systems in terms of posterior distributions of key parameters. The uncertainty in the simulated mineralization of organic N caused by parameter uncertainty was highlighted. Finally, we established and compared the average annual budgets of internal and external N-fluxes for each treatment.

2. Material and methods

2.1. Field site and management

The Mellby field trial (R0–8403) is a part of the Swedish University of Agricultural Sciences program for long-term field experiments (Bergkvist and Öborn, 2011). The field site is located in the southwest 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 annual precipitation of 812 mm (1984–2020 SMHIGridClim (Andersson et al., 2021)). The field site consists of 14 big experimental plots that are 40 × 40 m in size. The treatments were started in 1983 with the main purpose to gain insight into effects of different management practices, including mineral and organic fertilizers and cover crops on nutrient leaching, e.g. for the development of national legislation for agriculture. The topsoil is a sandy loam with a clay content of 5–10 % (Table 1) and an organic matter content of around 5 % at the start of the experiment (Lewan, 1994). The sand deposits (90–130 cm) are underlain by glacio-fluvial clay (Johnsson, 1991) which is more or less impermeable. Each plot is drained individually through tile drainage, with the tiles positioned at 0.9 m depth and spaced 7 m apart. Discard drainage pipes prevent lateral inflow from the surroundings.

Table 1
Soil characteristics and general management at Mellby.

Soil properties					
	Particle size distribution (%)				
	Clay (< 2 μm)	Silt (2–60 μm)	Sand (60 μm-2 mm)	Organic matter content (%)	pH
Topsoil (0–23 cm)	10.4	10.2	79.4	5.9	6.2
Subsoil (23–45 cm)	2.9	2.3	94.9	0.4	5.7
Management					
	Sowing	Fertilization	Harvest	Surface cultivation	Tillage
	April-May	~90 kg N ha^{-1} in spring	Aug-Sep, straw removed	Disc cultivator after harvest	20 cm Nov 4th- Dec 13th

Before the start of the experiment, the field received manure following agricultural praxis in Sweden, estimated at around 10–15 t ha^{-1} (fresh matter) every second to fourth year (Swedish Board of Agriculture, 2001). In this study, treatments supplied with or without mineral N fertilizer were used (not replicated). Spring cereals (wheat, barley, or oats) were grown in most years, with occasional crops of potatoes (3 years), spring oilseed rape (3 years), and triticale (1 year, sown in autumn) (Table S1). The fertilized treatment received 90–110 kg of mineral N ha^{-1} yr^{-1}, while both treatments received 20 kg P and 64 kg K ha^{-1} yr^{-1} until 2009. Thereafter, the unfertilized treatment no longer received P. The crops were sown in April and harvested in August (Table S1). The straw (cereals) was removed, whereas the potato haulm was chemically terminated two weeks before harvest and left in the field. Rapeseed straw was left in the field. The soil was surface cultivated (10–15 cm depth) with a disc cultivator shortly after harvest and plowed between November 4th and December 13th to 20 cm depth. Thereafter the soil was left bare over winter.

2.2. Field measurements and analyses

The drainage water from each plot was directed into an underground measuring station. The flow rate was measured with tipping bucket flow gauges, made of stainless steel with a volume of 4 L. The tips were registered by a pulse generator connected to a data logger, with continuous registration. Total N was measured by grab sampling every two weeks during 1984–1998. Thereafter, flow-proportional water sampling was used. For every 0.2 mm of drainage water entering the measuring station, 15 ml subsamples were pumped into plot-specific bottles. Every two weeks, when there was drainage, the bottles were emptied and water samples were taken and sent for analysis to accredited laboratories at the Swedish University of Agricultural sciences (at the Department of Soil and Environment until 2014 and thereafter to the Department of Aquatic Sciences and Assessment). Unfiltered water samples were used for the determination of total N and NO_3-N (also including NO_2-N) according to European standards (for total N: SIS 028131 until 2009, EN 12260–1 during 2010–2014 and SS-EN 12260–2 from 2014 and for NO_3-N + NO_2-N: SIS 028133–2 until 1997, SS-EN ISO 13395 during 1997–2014 and ISO 15923–1:2013 from 2014). Both total N and NO_3-N were analyzed colorimetrically, total N after oxidization to NO_3-N.

At the beginning of the experiment, both total N and nitrate-N (NO_3-N) were analyzed in the drainage water. Since 2012, only total N was measured. Therefore, a relationship between NO_3-N and total N was established for the data prior to 2012 with linear regression (intercept locked to zero, R^2 0.992, p-value <2.2e-16), to estimate NO_3-N concentrations. NO_3-N was found to be 90 % of the total N in solution. For the period with grab sampling, daily concentrations of total N and NO_3-N were obtained by linear interpolation between sampling events. However, for periods without drainage, e.g. during summer periods, the concentrations of the last sample before drainage ceased were used until the day when drainage stopped. For the period with flow-proportional water sampling, the measured concentration for each sampling period of two weeks was used every day during that period. NO_3-N load was calculated by the daily discharge multiplied by the daily concentration. Mean annual concentrations of NO_3-N were calculated by dividing annual accumulated leached NO_3-N by the annual drainage.

Grain, potato, straw, and haulm (not removed) yields were determined for three replicate samples in each plot with a known harvest area. Samples were dried at 60 °C and total N content was measured with an elemental analyzer (NA 1500 or LECO CNS-2000). We assumed that measured dry biomass consisted of 40 % C (Kröbel et al., 2011).

2.3. Climate data

Model driving data (daily air temperature, precipitation, and air humidity) was retrieved from a gridded database, SMHIGridClim (Andersson et al., 2021), provided by the Swedish Meteorological and Hydrological Institute, with a horizontal resolution of 2.5 km. For wind speed and global radiation, we used ERA5 (Hersbach et al., 2018), which has a horizontal resolution of 0.25° x 0.25° (~28 km). A Mann-Kendall test was performed to check for trends in each variable.

2.4. Model description and model setup

CoupModel version 6.2.5 was used in this study (Jansson and Karlberg, 2004; Jansson, 2012; He et al., 2021). The core of the model is the coupling of two differential equations for heat and water, derived from Fourier's and Darcy's law, respectively. The model structure can be adjusted by the user to suit specific needs through a series of options. Water retention was expressed using the function of Brooks and Corey (Brooks and Corey, 1964) and unsaturated hydraulic conductivity following Mualem (Mualem, 1976). The soil profile was described by 12 layers with thicknesses of 5, 10, 15, 20, and 30 cm at depths of 0–5, 5–15, 15–90, 90–110 and 110–230 cm, respectively. Water flow through the drainage pipes was expressed by the Hooghoudt drainage equation (Hooghoudt, 1940). The bottom layer, which was nearly impermeable, due to the glacio-fluvial clay layer, was represented by a seepage equation (Table S2) where the outflow is given as a function of water table depth and the depth of a theoretical drain depth and spacing. The Penman-Monteith equation (Monteith, 1965) was used to simulate transpiration from the plant cover and for soil evaporation. Partitioning of net radiation between the leaf canopy and soil followed Beer's law. The water and heat flows drive the carbon and nitrogen at every time step. The abiotic environment interacts dynamically with plant growth, which was modeled with an "explicit big leaf" approach. Plant growth is divided into four growth stage indices (GSI), starting with emergence followed by grain filling, maturation, and finally harvest. GSI is either estimated as a function of temperature sums or is given as Julian days by the user. In this study, the sowing, emergence and harvest dates were specified as Julian days. N allocation is controlled by the N demand of the leaf, root, and stem (Table S2). C allocation fractions to roots and leaf were set to constant values. The remaining fraction was allocated to stems. When grain filling starts, C and N is allocated to the grain from all plant compartments.

Harvest of potatoes was simulated in the same way as grains, but the potato haulm was left on the field and plowed down, to account for the green manuring by plant residues. The soil organic C and N were represented by a slow pool (called humus pool in the model), a litter pool, and an inert pool. The litter pool represents fresh organic material and has a higher turnover rate than the slow pool. The soil organic matter (SOM) in the slow pool has a slower turnover rate due to both physical protection and chemical stability of the material. Decomposition is modeled assuming first-order kinetics.

2.5. Parameterization, initialization, and model calibration

Since a predecessor of the CoupModel (SOIL-SOILN, Lewan, 1993; Lewan, 1994 and Blombäck et al., 2003) was applied to the same field site (but for limited periods <7 years and on other plots), we could make use of previous calibrations to set some parameters (Table 2). Values for the Brooks-Corey-Mualem hydraulic parameters in each layer were taken from Lewan (1993) based on Johnsson (1991). Soil samples for C and N measurements were taken in 1988 at 0–30, 30–60, and 60–90 cm depths. We used the average values for each depth, from 10 different plots with different treatments as initial values and used interpolation to make the data compatible with the soil layers used in the model (Table S3). The C/N ratio was 19.2 in the topsoil (0–30 cm), 25.4 at 30–60 cm depth, and 24.2 at 60–90 cm depth. Before the end of the 19th century, the site was most likely a heathland that was grazed and subjected to burning (Frisk and Larsson, 1999), which would explain the unusually high C/N ratio (a value of around 10 is more common in agricultural soils in Sweden; Eriksson et al., 2010). Springob and

Table 2
Key parameters with fixed values during the calibration.

Parameter	Value	Unit	Explanation	References
			1. Crop parameters	
CN LOpt	8.9	-	Optimum C-N ratio in leaves for photosynthesis.	Wu et al., (1998)
CN ratio min Leaf	8	-	CN ratio to calculate N demand	Blombäck et al., (2003)
CN ratio min roots	25	-	CN ratio to calculate N demand	Default
CN ratio min stem	25	-	CN ratio to calculate N demand	Default
Root Mass c1	0.4	-	Fraction of the mobile carbon assimilates allocated to the roots in the response function for nitrogen concentration in leaves.	Salo et al., (2016)
CondRis	5×10^6	J m^{-2} day^{-1}	The global radiation intensity that represents half-light saturation in the light response.	Default
CondVPD	1100	Pa	The vapour pressure deficit that corresponds to a 50 % reduction of stomata conductance	Blombäck et al., (2003)
RespTemQ10Bas	20	°C	Base temperature for the plant respiration at which the response is 1	Johnsson et al., (1987)
WaterCapacityPerLAI	0.2	mm	Interception storage capacity per LAI unit.	Lewan, (1993)
RntLAI	0.5	-	Extinction coefficient	Johnsson and Jansson, (1991)
			2.Litter and respiration	
Eff humus	0.5	-	Efficiency of the decay of humus	Johnsson et al., (1987)
Eff litter	0.5	-	Efficiency of the decay of litter	Johnsson et al., (1987)
RateCoefLitter	0.035	day^{-1}	Rate coefficient for the decay of litter	Default
RateCoefInert	10^{-7}	day^{-1}	Rate coefficient for the inert pool	
			3. Soil parameters	
AlbedoDry,	25	%	Albedo of a dry soil	Lewan, (1993)
AlbedoLeaf	25	%	Albedo of leaf	Lewan, (1993)
DenitNitrateHalfSat	10	mg N L^{-1}	Half saturation constant in function for nitrate concentration effect on denitrification.	Johnsson et al., (1987)
DenitPotentialRate	0.4	g N m^{-2} day^{-1}	The potential rate of denitrification.	Default
NitricSpecificRate	0.2	day^{-1}	Nitrification rate under optimal moisture and temperature conditions	Johnsson et al., (1987)
RoughLBareSoilMom	0.01	m	Minimum value of roughness length, valid when the soil is bare	Assumed
Saturation activity	0.6	-	Saturation activity in soil moisture response function.	Johnsson et al., (1987)
T Lmin	5	°C	Threshold temperature for the microbial activity, mineralisation-immobilisation, nitrification and denitrification below which the response is more strong than above and ceases at 0 °C.	Bergström and Johnsson, (1988)

Kirchmann (2002) found that 74.8 % of the SOC at Mellby was HCl-resistant, suggesting that it is highly recalcitrant. They found similar results across a range of soils in northern Europe, which have been under similar historical land management ("plaggen" or heathland). To account for the fraction of inert SOM, we followed the advice given by Springob and Kirchmann (2010) and considered the active pool to have a C/N ratio of 10 and the inert pool a C/N ratio of 35 (Table S3). The decomposition rate constant for the inert pool, accounting for 71 % of the total SOC and 41 % of the total SON was set to such a low value (10^{-7} day^{-1}) that decomposition was near zero.

To allow the litter pool to stabilize, the first simulated year (1984) was run twice. We supplied the model with all available field management records, including dates of tillage, fertilizer application, sowing, emergence, and harvest (Table S1).

To calibrate the model and to account for parameter uncertainty we selected 16 parameters representing different parts of the agroecosystem that were considered important for this study based on expert knowledge and former model applications (Table 3). The model was run 10,000 times with the parameter values randomly sampled from uniform prior distributions (Table 3). Among the available measurements that we could use to constrain the model, we identified annual total N leaching (g NO_3-N m^{-2}), tile drainage (mm), N content in grain and dry grain yield (g m^{-2}), and total aboveground biomass (dry matter) and N at harvest (g m^{-2}) to be the most important for satisfactory simulations of the two treatments. Calculated leaching of NO_3-N was preferred over measured concentrations due to the method used for water sampling (flow-proportional from 1998) where the NO_3-N concentrations were integrated over sampling periods to get the best possible estimates of the total leaching losses.

The prior ranges of the parameters in the calibration were adjusted until the mean error of the validation variables was as centered around zero as possible. This was to minimize bias in the prior distribution. Bias in the posterior distributions are therefore primarily a result of trade-offs between the different output variables used in the calibration. RMSE was used as an objective function to constrain N transport and drainage based on yearly accumulated data (Table 4). Using RMSE (Eq. 1) on accumulated values has the benefit that daily values are down-weighted while seasonal patterns are still considered. It was not considered important that the model captured the exact timing (day) of N leaching, but rather the cumulative yearly amount. We then used R^2 and ME (Eq. 2) to further improve the fit of grain yield, and aboveground harvest and their respective N content. To evaluate the model performance, the

Table 3
Parameters which were included and varied in the Monte-Carlo calibration procedure.

Parameter	Min/max	unit	Symbol	Function
CLeaftoGrain	0.01/0.04	-	$a_{C,lg}$	Fraction of carbon in leaves reallocated to grains during grain development
CStemtoGrain	0.01/0.04	-	$a_{C,sg}$	Fraction of carbon in stem reallocated to grains during grain development
CNLTh	60/100	-	$p_{CN,Th}$	Threshold above which no photosynthesis occurs
ConductMax	0.01/0.04	m s^{-1}	g_{max}	The maximal conductance of a fully open stomata
CritThresholdDry	50/200	cm water	Ψ_c	Critical pressure head for reduction of potential water uptake
DrainSpacingLowerB	10/15	m	d_{p2}	Distance between assumed drainage system for calculation of deep percolation.
FlexibilityDegree	0.02/0.6	-	f_{umov}	A compensatory uptake of water will be calculated if a deficiency occurs because of too high water tensions at some layers in the soil profile simultaneously as the water tension is below the critical threshold at other layers
Leafc1	0.3/0.4	-	l_{c1}	Fraction of the mobile carbon assimilates allocated to the new shoots
NLeaftoGrain	0.02/0.05	-	$a_{N,lg}$	Fraction of nitrogen in leaves reallocated to grains during grain development
NStemtoGrain	0.02/0.05	-	$a_{N,sg}$	Nitrogen flux from stem to grain.
NUptFlexibilityDeg	0.2/0.6	-	$n_{Uptflex}$	Compensatory N uptake from layers with excess of N.
RadEfficiency	1.5/3	gDw MJ^{-1}	ε_L	Radiation use efficiency for photosynthesis at optimum temperature, moisture and C-N ratio.
RateCoefHumus	5×10^{-5} /4×10^{-4}	day^{-1}	K_h	Rate coefficient for the decay of humus (slow pool).
LeafMassPerArea	10/20	gC m^{-2}	$P_{l,sp}$	Parameter to convert leaf C mass into leaf area
ThetaLowerRange	5/13	vol%	$P_{\theta Low}$	Water content interval in the soil moisture response function for microbial activity, mineralisation-immobilisation, nitrification and denitrification.

Table 3 (*continued*)

Parameter	Min/max	unit	Symbol	Function
Humfraclitter	0.1/0.3	gC gC^{-1}	$f_{h,l}$	Fraction of carbon and nitrogen contained in the litter pool of the soil that will enter the humus pool

Nash-Sutcliffe model efficiency coefficient (NSE) was used (Eq. 3).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(yi - \widehat{y}i)^2} \quad (1)$$

$$ME = \frac{1}{n}\sum_{i=1}^{n}(\widehat{y}i - yi) \quad (2)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(yi - \widehat{y}i)^2}{\sum_{i=1}^{n}(yi - \overline{y})^2} \quad (3)$$

where n is the total number of measurements, y_i is the measured value for the i^{th} measurement,

$\overline{y}$ is the average of the measured value, and $\widehat{y}i$ is the simulated value for the i^{th} measurement.

The 30 best ("accepted") model runs obtained for each treatment were used to compare the mineralization dynamics between treatments and their average annual N budgets. N budgets were calculated based on the mean values of the 30 accepted simulations. A Mann-Kendall test was performed on the mean annual values of the 30 accepted simulations and for the measurements, to test for trends in annual discharge, NO_3-N concentration, NO_3-N leaching, N mineralization, and yield.

3. Results

3.1. *Trends in climate data*

The Mann-Kendall test was significant ($P < 0.05$) for the average annual temperature, with an increase of 0.06 °C yr^{-1} (Table 5). While all the other climate variables also had positive slopes, none of them were significant.

3.2. *Model calibration and model performance*

3.2.1. *Constrained parameter ranges*

The criteria used in the calibration substantially reduced the prior parameter ranges for most parameters (Fig. 1). There were significant differences in parameter ranges between the fertilized and unfertilized treatments for 6 of the 16 parameters. The unfertilized treatment had a higher mean value of the *RateCoefHumus* parameter (K_h) (rate coefficient in the degradation function for organic matter in the slow pool, eq 9 in Table S2), *LeafMassPerArea* ($P_{l,sp}$) (parameter to convert leaf C mass into leaf area, eq 8 in Table S2) as well as *NUptFlexibilityDeg* ($n_{Uptflex}$) (compensatory N uptake from layers with excess of N, eq 7 in Table S2) and *CritThresholdDry* (Ψc) (critical pressure head for reduction of potential water uptake, eq 12 in Table S2). However, *CLeaftoGrain* ($a_{C,lg}$) and *CStemtoGrain* ($a_{C,sg}$) (fraction of carbon in leaves and stem reallocated to grains during grain development, Eq. 1 in Table S2) were higher in the fertilized treatment.

There were some trade-offs in the calibration, which led to certain biases in the posterior distributions (Table 6). In the fertilized treatment, ME was above zero for N total harvest for all the accepted simulations although some candidates in the prior were below zero. In the unfertilized treatment, N total harvest showed less bias. However, ME for N grain was below zero for the vast majority of accepted runs. At the same time, ME for NO_3-N leaching was above zero for all accepted runs. There

Table 4
Threshold limits used in the calibration and their removal efficiency on the total number of simulations (10,000).

Measured variable	Unit	Data points	RMSE max	R^2 min	ME min	max	No. of remaining runs	Efficiency of rejection (%)
Fertilized treatment								
NO_3-N leaching	mg L^{-1}	13134	2	-	−0.0014	0.0014	2907	71
Drainage	mm	13134	50	-	−0.12	0.12	9550	4
Grain yield	g C m^{-2}	36	-	0.4	−100	100	965	90
Aboveground harvest	g C m^{-2}	19	-	-	−125	125	4984	50
N grain harvest	g N m^{-2}	36	-	0.43	−1.2	1.2	2176	78
N total harvest	g N m^{-2}	19	-	-	−2	2	3934	61
Unfertilized treatment								
NO_3-N leaching	mg L^{-1}	13134	0.8		−0.0014	0.0014	3741	63
Drainage	mm	13134	50		−0.12	0.12	9412	6
Grain yield	g C m^{-2}	36	-	0.2	−75	75	3820	62
Aboveground harvest	g C m^{-2}	19	-	-	−100	100	7137	29
N grain harvest	g N m^{-2}	36	-	0.08	−0.4	0.4	199	98
N total harvest	g N m^{-2}	19	-	-	−2	2	9855	1

Table 5
Mann-Kendall trend test of the weather variables for the period 1984–2020. A tau value of one ($\tau = 1$) means that the trend is perfectly monotonous and increasing. Theil Sen's slope represents the trend. Only temperature showed a significant trend ($P < 0.05$).

	Tau (τ)	Theil Sen's slope	P value
Temperature (°C yr^{-1})	0.45	0.06	9.20E−05
Humidity (% day^{-1})	0.192	0.05	0.1
Windspeed (m s^{-1} day^{-1})	0.129	0.003	0.3
Global radiation (J m^{-2} day^{-1})	0.195	10564	0.1
Precipitation (mm yr^{-1})	0.0661	1.3	0.6

were no clear trade-offs between the variables in terms of temporal dynamics, and R^2 generally increased or remained largely unchanged in the posterior distributions except for NO_3-N leaching in the fertilized treatment and N total harvest in the unfertilized treatment.

3.2.2. Discharge, NO_3-N concentration and NO_3-N leaching in drainage water

The model reproduced yearly drainage rather well for both treatments (NSE was 0.67 ± 0.04 and 0.65 ± 0.04 in the fertilized and unfertilized, respectively). However, the model failed to reproduce the unusually high drainage in a few individual years, e.g. in 1988 and 2002 (Fig. 2A).

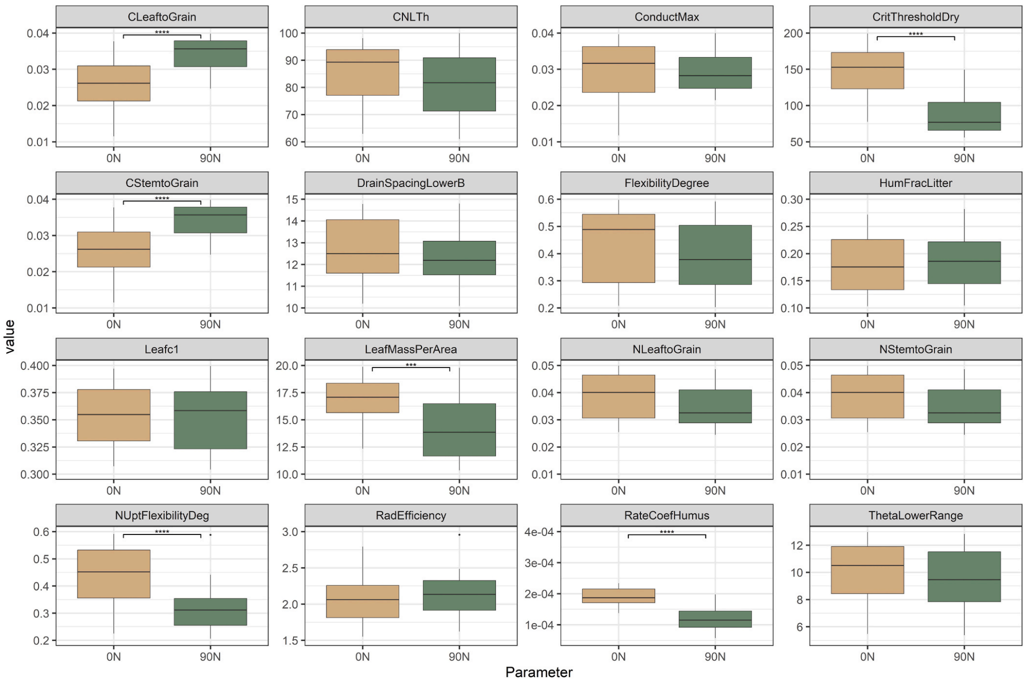

Fig. 1. Posterior ranges and medians of the accepted parameter values included in the Monte-Carlo calibration procedure, for the fertilized (0 N) and unfertilized (90 N) treatments. Vertical lines show the min./max. values of the prior ranges. Significant differences between treatments are represented by stars (****=$p < 10^{-4}$).

Table 6
Model performance based on yearly cumulative values, before and after calibration, for selected output variables.

Performance index	Variable	Fertilized (90 N)		Unfertilized (0 N)	
		Prior	Posterior	Prior	Posterior
ME	NO_3-N leaching	0.002 ± 0.006	−0.0003 ± 0.001	0.002 ± 0.002	0.001 ± 0.0004
	Drainage	−0.01 ± 0.06	0.02 ± 0.06	−0.003 ± 0.07	−0.03 ± 0.04
	Grain yield	−12.28 ± 143.68	−35.73 ± 41.01	7.03 ± 65.63	7.23 ± 35.18
	Aboveground harvest	50.43 ± 179.85	−39.73 ± 52.95	1.13 ± 90.45	−0.78 ± 34.38
	N grain harvest	−0.03 ± 1.72	−0.39 ± 0.47	−0.44 ± 0.7	−0.25 ± 0.14
	N total harvest	2.36 ± 1.48	1.66 ± 0.26	0.00 ± 0.99	0.12 ± 0.19
R^2	NO_3-N leaching	0.46 ± 0.05	0.42 ± 0.04	0.38 ± 0.05	0.37 ± 0.03
	Drainage	0.82 ± 0.01	0.83 ± 0.01	0.82 ± 0.01	0.81 ± 0.01
	Grain yield	0.34 ± 0.09	0.44 ± 0.02	0.20 ± 0.06	0.24 ± 0.03
	Aboveground harvest	0.09 ± 0.07	0.19 ± 0.05	0.04 ± 0.07	0.04 ± 0.03
	N grain harvest	0.40 ± 0.07	0.46 ± 0.02	0.06 ± 0.02	0.08 ± 0
	N total harvest	0.03 ± 0.03	0.02 ± 0.02	0.06 ± 0.06	0.01 ± 0.02
RMSE	NO_3-N leaching	1.55 ± 0.72	1.25 ± 0.07	0.90 ± 0.27	0.72 ± 0.03
	Drainage	41.55 ± 1.84	40.5 ± 1.31	41.96 ± 2.14	41.83 ± 1.38
	Grain yield	179.8 ± 59.85	123.18 ± 10.65	113.28 ± 23.98	98.58 ± 6.78
	Aboveground harvest	231.50 ± 83.18	160.18 ± 11.6	148.4 ± 31.63	122.45 ± 5.18
	N grain harvest	2.17 ± 0.71	1.52 ± 0.11	1.31 ± 0.26	1.06 ± 0.03
	N total harvest	3.05 ± 1.1	2.18 ± 0.21	1.68 ± 0.3	1.35 ± 0.03

The ensemble mean of simulated annual NO_3-N -concentrations in drainage water from the fertilized treatment was generally below the annual average of observed concentrations (10.81 ± 1.2 compared to 13.1 mg L^{-1}). On the contrary, the ensemble mean concentration for the unfertilized treatment was systematically higher than the observed mean (7.69 ± 0.73 compared to 6.53 mg L^{-1}). The between-year variations in annual mean NO_3-N concentrations were not very well reproduced by the model and NSE was negative for both treatments (-0.36 ± 0.24 and −0.08 ± 0.25 in the fertilized and unfertilized treatments respectively), see also Fig. 2B.

The observed annual NO_3-N leaching was on average more than twice as high in the fertilized treatment compared to the unfertilized over the whole period (3.7 compared to 1.8 g NO_3-N m^{-2} yr^{-1}). The corresponding ensemble mean of the simulated annual NO_3-N leaching for the fertilized and unfertilized treatments were 2.7 ± 0.3 and 1.9 ± 0.1 g NO_3-N m^{-2} yr^{-1}, respectively). The between-year variation in average annual nitrate concentrations was better captured for the unfertilized treatment compared to the fertilized (NSE was 0.12 ± 0.07 and-0.03 ± 0.12, respectively), Fig. 2C.

The summer of 2018 was exceptionally dry, with only 9.5 mm of rainfall in May, 25.7 mm in June, and 6.8 mm in July. Interestingly, all accepted model runs reproduced the annual NO_3-N leaching well in both 2018 and the following year in both treatments. This indicates that the model captured a carry-over effect in terms of high NO_3-N concentrations and leaching early in 2019, in response to the extremely dry summer and thus poor N uptake by the crop in 2018.

3.2.3. Trends in NO_3-N leaching, drainage and NO_3-N concentration

No significant trend in drainage was detected in the measurements or simulations for any of the treatments. The measured NO_3-N leaching showed a small, yet significant, decrease in both treatments and Sen's slope was −0.09 and −0.05 g NO_3-N m^{-2} yr^{-1} in the fertilized and unfertilized treatments, respectively. In the simulations, there were no significant trends for NO_3-N leaching. All simulations and measurements showed a significant decrease in mean annual NO_3-N concentration in both treatments. In the fertilized treatment, Sen's slope was −0.24 mg L^{-1} yr^{-1} for the measurements and on average −0.12 ± 0.04 mg L^{-1} yr^{-1} for the simulations. In the unfertilized treatment, Sen's slope was −0.23 mg L^{-1} yr^{-1} for the measurements and on average −0.1 ± 0.02 mg L^{-1} yr^{-1} for the simulations.

3.2.4. Grain yield and N grain

The measured grain yield was on average 2.2 times larger in the fertilized treatment (408 compared to 188 g m^{-2}). Similarly, the N in the harvested grain (N grain) was 2.6 times larger in the fertilized treatment (6.6 compared to 2.5 g N m^{-2}) (Fig. 3). The mean simulated grain yield was slightly overestimated for both treatments (455 ± 70 and 200 ± 35 g m^{-2} in the fertilized and unfertilized, respectively). The mean simulated N grain was slightly overestimated for the fertilized and slightly underestimated for the unfertilized (6.8 ± 0.6 and 2.3 ± 0.15 g N m^{-2} for the fertilized and unfertilized, respectively). The between-year variations in grain yield and N grain were better captured for the fertilized treatment (Table 6). In 2005, when triticale was grown, the observed harvest was surprisingly high in the unfertilized treatment but remained at a normal level in the fertilized treatment. In 1995 when rapeseed was grown, the observed harvest was exceptionally low in the unfertilized treatment. Observed N grain showed a small but significant downward trend (Sen's slope was −0.07 g N m^{-2} yr^{-1}) for the fertilized treatment. Only four of the model runs showed a significant trend (Sen's slope was −0.03 g N m^{-2} yr^{-1}). The simulations also indicated a weak but significant trend in N grain for the unfertilized treatment (Sen's slope −0.01 g N m^{-2} yr^{-1}). Grain yield showed a decreasing trend only in two simulations for the fertilized treatment (Sen's slope −2.25 g m^{-2} yr^{-1}). For the unfertilized treatment, all simulations showed a significant downward trend (Sen's slope was −2.1 g m^{-2} yr^{-1}).

3.2.5. Below-ground allocation of dry matter and N

The simulated dry matter and N allocated below-ground were slightly higher in the unfertilized treatment compared to the fertilized treatment. The percentage of total dry matter found in the roots at the time of harvest was 27 ± 2 % in the fertilized treatment and 29 ± 1 % in the unfertilized treatment. The corresponding values for N were 30 ± 3 % and 33.3 ± 3 % for the fertilized and unfertilized treatments, respectively.

3.3. Evolution of soil organic N and annual N mineralization

Soil organic N (SON) declined in all simulations for the unfertilized and in 23 of 30 model runs for the fertilized treatment (Fig. 4). According to the simulations, the change in SON by mineralization during the whole period was −8.8 ± 14.7 and −121.4 ± 11.3 g N m^{-2} in the fertilized and unfertilized treatment respectively.

The fertilized treatment showed a higher uncertainty in the simulated annual N mineralization. The difference between the minimum and maximum values varied between 2.5 and 5.6 g N m^{-2} yr^{-1} compared to 1.7–3.4 g N m^{-2} yr^{-1} in the unfertilized treatment (Fig. 5). There was a substantial overlap with the range obtained for the unfertilized treatment. Nevertheless, the fertilized treatment showed

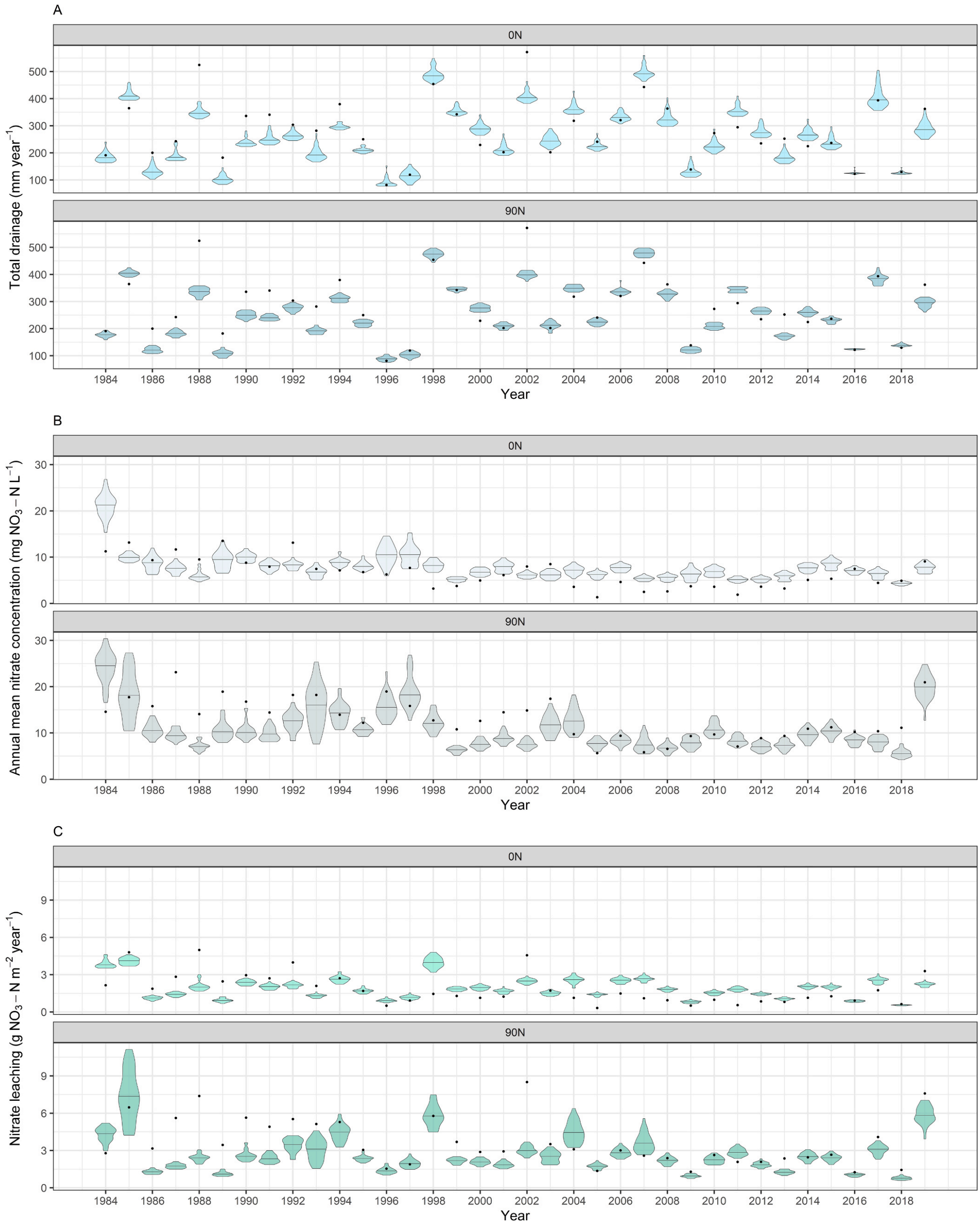

Fig. 2. Annual total drainage (mm yr^{-1}) (A), annual mean nitrate concentration (mg NO_3-N L^{-1}) (B), and annual nitrate leaching in the drainage water (g NO_3-N m^{-2}) (C) for the fertilized (90 N) and unfertilized (0N) treatments , 1984–2019. Dots represent values based on observations and the violin plots represent the results from the 30 best/accepted model-runs for each treatment. The horizontal line is the median value.

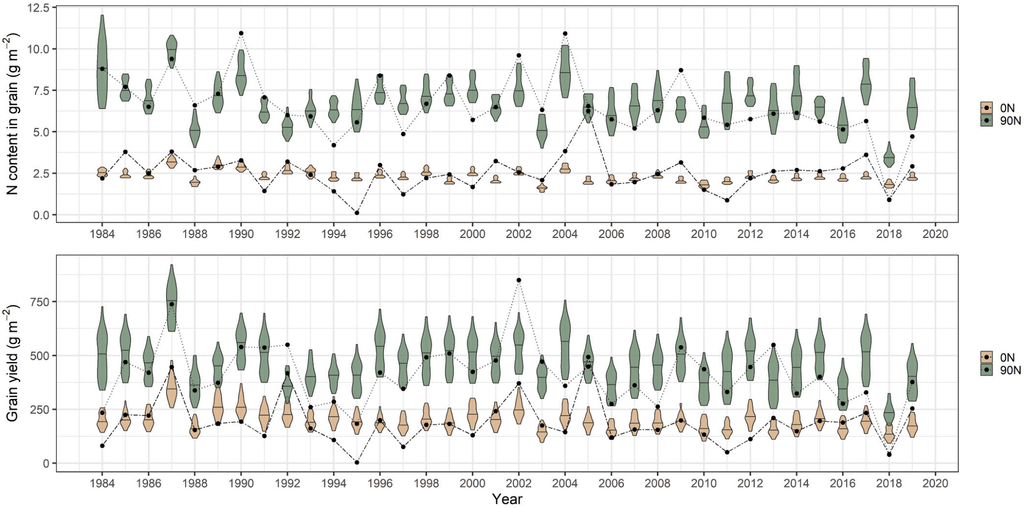

Fig. 3. Yield (g m^{-2}) and nitrogen content (g N m^{-2}) in the harvested grains/tubers/seeds for the fertilized (90 N) and unfertilized (0 N) treatments. Dots represent observations and violin plots represent the results from the 30 best/accepted model-runs for each treatment. The horizontal line is the median value.

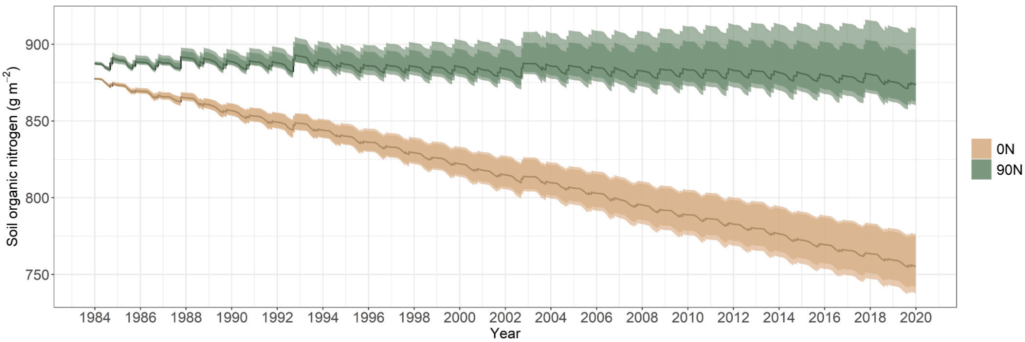

Fig. 4. Simulated soil organic nitrogen (g m^{-2}) for the unfertilized (0 N) and fertilized (90 N) treatments (1984–2019), with median (thick line) and 50 and 95 % uncertainty bands, based on the 30 best/accepted model runs for each treatment.

consistently higher median values. This was especially true for the years following a potato crop (1988, 1993, 2003). In the fertilized treatment, there was no significant trend in the annual total N mineralization. In the unfertilized treatment, there was a decreasing trend in 21 of the accepted model runs, and Sen's slope was −0.02 g N m^{-2} yr^{-1}. The model thus indicates that 0.7 g m^{-2} less N is mineralized per year after 35 years in the unfertilized treatment.

3.4. Simulated mean annual nitrogen balance

Simulated yearly N balances were negative for both treatments (Table 7). The export of N by nitrate leaching was on average 1.4 times larger in the fertilized plots compared with the unfertilized. However, the yield-scaled losses (N leached per unit of N harvested) were larger in the unfertilized treatment than in the fertilized (0.57 compared to 0.29 g N/ g N) due to the smaller yields. The simulated total harvested N (straw and seed) was 2.8 times greater in the fertilized treatment (Table 7). Table 7 also shows that the amount of N lost by deep leaching (nitrate that passes the depth of tile drains) and denitrification was small and similar in both treatments. In the fertilized treatment, more organic N entered both the slow pool (humus formation) and the litter pool, while less N was mineralized from the slow pool compared to the unfertilized treatment. More litter was also produced, both above- and below-ground. However, litter mineralization was also higher in the fertilized treatment (Table 7).

4. Discussion

In this study, we tested and evaluated the performance of a frequently used soil-vegetation model (CoupModel) with respect to two contrasting fertilization treatments in southern Sweden, over a 35-year time period which also covered a significant trend in temperature of 0.06 °C yr^{-1} and one growing season with unusually high temperatures and extremely low rainfall (2018). The model was separately calibrated

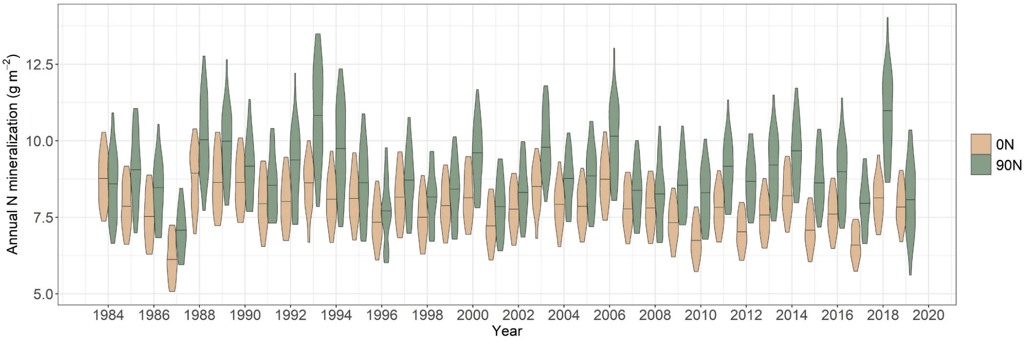

Fig. 5. Simulated annual N mineralization (g m^{-2}) for the fertilized (90 N) and unfertilized (0 N) treatments. Violin plots show the distributions of results from the 30 best/accepted model-runs for each of the treatments. The horizontal line is the median value of the ensemble.

Table 7
Yearly N balance (g N m^{-2}) calculated from the ensemble of the 30 best/accepted model runs for the fertilized and unfertilized treatment (90 N and 0 N), based on 35 years (1984–2019).

		Fertilized (90 N)	Unfertilized (0 N)
Input	Fertilization	10.32	0
	Deposition	1.53 ± 0.004	1.52 ± 0.004
	Seeds	0.53	0.53
Σ		**12.35 ± 0.03**	**2.06 ± 0.004**
Export	Nitrogen Harvest	−9.64 ± 0.33	−3.46 ± 0.2
	Min N Leaching	−2.75 ± 0.32	−2.03 ± 0.13
	Deep N leaching	−0.16 ± 0.03	−0.16 ± 0.03
	Denitrification	−0.2 ± 0.01	−0.18 ± 0.01
Σ		**−12.74 ± 0.41**	**−5.83 ± 0.32**
Storage			
	Soil organic N	−0.28 ± 0.42	−3.48 ± 0.32
	Mineral N	−0.23 ± 0.02	−0.30 ± 0.02
Σ		**−0.51 ± 0.42**	**−3.78 ± 0.32**
Organic transformation			
	Humus formation	3.54 ± 0.99	2.23 ± 0.6
	Humus mineralisation	−3.76 ± 1.09	−5.59 ± 0.77
	Aboveground input to litter	2.24 ± 0.38	1.62 ± 0.19
	Belowground input to litter	6.70 ± 0.64	2.96 ± 0.31
	Litter mineralisation	−5.13 ± 0.92	−2.20 ± 0.57

on data from each of the treatments (spring cereals on sandy soil, with and without N fertilizer). The obtained differences between the treatments in key parameter values and simulated outputs are discussed below with a focus on long-term crop yields, nitrate leaching, and soil nitrogen dynamics.

4.1. Grain yield and N grain

No significant trends were identified in observed grain yield or N in harvested grain in the unfertilized treatment. Generally, it seems that after an initial drop in yield of about 250 g m^{-2}, the unfertilized system was able to sustain this lower yield level for a considerable time (>30 years) as a consequence of the mineralization of organic N. In contrast, the model simulations did suggest a small decreasing trend for both grain yield and N in grain in the unfertilized treatment due to the decreasing trend in net N mineralization. That this trend was not significant in the observations may be due to additional factors affecting yields in individual years that are not accounted for by the model (e.g. pathogens, pests, and diseases (Bregaglio et al., 2021)).

The model reproduced a reduction in yield observed in both treatments in 2018 due to extremely low rainfall amounts and high temperatures during the growing season, although the extent of the reduction was not as great as in the measurements (65–223 g m^{-2} in the simulations compared to 150–379 g m^{-2} in the measurements). There may be several reasons for this, but a plausible explanation is that the model underestimated the effects of combined water and heat stress or that it does not consider certain plant responses to water or heat stress, such as an earlier onset of heading and flowering. Improving predictions of phenology as a function of climate is therefore an important task for future research (Wallach et al., 2023).

4.2. Results of the calibration

The calibration resulted in significant differences between the two treatments in the posterior values and ranges of some critical parameters. The smaller value of *LeafMassPerArea* indicates thinner leaves following N fertilization, which is supported by previous studies (e.g. Knops and Reinhart, 2000). To reproduce the observed yields, *CleaftoGrain and CStemtoGrain* were required to be higher in the fertilized treatment, while *CritThresholdDry and NUptFlexibilityDeg* were lower. The model thus suggests, as expected, that the crop in the fertilized treatment shows less sensitivity to N stress. At the same time, the fertilized treatment showed a higher sensitivity to water stress (lower *CritThresholdDry)* which might be consistent with a higher transpiration rate from a larger leaf area and above ground biomass.

CoupModel does not come with any ready-to-use crop-specific parameterizations that are included in other models such as APSIM and STICS (Brisson et al., 2009; Keating et al., 2003). Such templates are typically developed from detailed field experiments with measurements of several phenological variables. However, such field experiments are scarce at higher latitudes, where both growing conditions and cultivars differ (Kumar et al., 2021). In this regard, allowing key allocation parameters to vary during calibration was seen as a viable alternative. Indeed, crop yields during the 35 years were reproduced with satisfactory accuracy by the mean of the 30 best simulations in both fertilized and unfertilized treatments, even though we did not distinguish between crops, other than the fact that potato haulm was left on the field. This simplification most likely contributed to some of the deviations between the simulated and measured yields in single years (Fig. 3). Furthermore, the allocation coefficients and critical N concentrations were kept constant during the growing season which caused the stem to have a lower C/N ratio at the time of harvest than is normal for spring cereals (30 and 50 for the fertilized and unfertilized, respectively). This was likely the reason behind the trade-offs between N total harvest, N grain, and nitrate leaching seen in the calibration (Table 6). The allocation of C and N to roots may also have been an important source of error in the simulations. Hansson et al. (1987) found root biomass at harvest for a barley crop to be 16 % and 23 % of total biomass and N in roots to be 21 % and 28 % of total N content for a fertilized (120 kg N/ha) and unfertilized treatment, respectively. The simulated values for root biomass obtained in this study (27 $\pm$ 2 % and 29 $\pm$ 1 % of total biomass) and N in roots (30 $\pm$ 3 % and 33 $\pm$ 3 % of total N content for the fertilized and unfertilized, respectively) thus seem to be at the higher end for both root biomass and N. Future model applications would benefit from the development of crop-specific allocation patterns based on datasets that contain more data on root biomass and phenology.

4.3. Drainage and nitrate leaching

The calibrated model simulated drainage and nitrate leaching satisfactorily for both treatments in most years (Fig. 2). In the first 11 years, the observed nitrate leaching in the unfertilized treatment was systematically higher compared with the subsequent years. This may be due to the history of the field site where farmyard manure had been applied for a long time. Additionally, until 1998, grab sampling was used instead of flow proportional sampling. Grab sampling has been found to give higher N concentrations (Stone et al., 2000). This change in measurement method may have caused a trade-off between the two periods in the parameterization of the model.

4.4. Soil organic nitrogen dynamics

The model indicates a faster degradation of organic matter (a higher value for the parameter *RateCoefHumus*) in the unfertilized treatment compared to the treatment supplied with mineral fertilizer (Fig. 1 & Figs. 4–5). This may indicate a difference in the composition and type or function of microbial communities between the two treatments. Spohn et al. (2016) found that N fertilization reduced microbial respiration in a temperate grassland in Austria. Similarly, Janssens et al. (2010) found a decrease in forest soil respiration following N deposition. N fertilization may increase the relative contribution of root-derived C to microbial biomass and reduce soil organic matter losses (Zang et al., 2017) as well as promote conversion of mineral N to organic N (Liang et al., 2022). The *RateCoefHumus* parameter was relatively well-constrained in both treatments (Fig. 1). However, in the fertilized treatment there was a larger spread in simulated mineralization and the development of SON was less certain, and positive instead of negative for seven of the accepted model runs (Figs. 4–5). This was likely because the variables used for the calibration were not as sensitive in the fertilized treatment as in the unfertilized. Adding mineral fertilizer to the system thus allowed for a broader range of parameter value combinations, and will therefore require additional types of observations to constrain the model efficiently. Calibration against reliable estimates of SOC or SON, which are often missing in many field studies, would be necessary to further constrain the mineralization. Large uncertainties in the simulation of N mineralization were also found in a model comparison study in northern France (Yin et al., 2020b). Thus, both model uncertainty and parameter uncertainty might contribute to the overall uncertainty in modeled mineralization of nitrogen in arable soils, which makes predictions of N mineralization in response to changed management or climate highly uncertain, despite calibration against long-term data sets including key variables such as yield and nitrate leaching.

The high C/N ratio (varying from 19 to 25) at the field site posed a challenge for the initialization of the organic pools. We opted for the recommendation given by Springob and Kirchmann (2010) and considered the slow pool to have a C/N of 10 and the inert pool a C/N ratio of 35. The parameter *CN microbe*, representing the C/N ratio of microbial biomass and "humified" products was set to its default value of 10. With this setup, the C/N ratio of the slow pool did not change over time. Assuming an additional pool to be inert as was done here, seems to be a good solution for this type of old heathland soil. However, other solutions might be required for soils with high C/N originating from other land use histories, and thereby other types of particulate organic matter.

5. Conclusions

Long-term field measurements of yield and nitrate leaching in fertilized and unfertilized cropping systems provided robust support for the calibration of a process-oriented agroecosystem model with respect to a period covering a systematic trend in the climate (air temperature) as well as an extreme year (2018) with severe drought. It allowed us to establish and compare the budgets of internal and external fluxes of nitrogen in the two systems over more than three decades and also to identify where the model structure and parameterization could be improved.

Yields, drainage, and nitrate leaching were generally well captured by the model during the 35 years. The model simulated substantial yield reductions in the severe drought year of 2018 in both treatments, although not to the extent indicated by the measurements. This highlights the importance of model testing and model improvements to accurately account for the combined impact of both water and heat stress on crop yields in exceptionally hot and dry years. Moreover, our study suggests that the representation of year-to-year variations could be improved by developing crop-specific parameterizations in Coup-Model, in particular with respect to phenology and the allocation of assimilate to above- and below-ground biomass.

Separate long-term calibrations of the fertilized and unfertilized cropping systems resulted in substantially different posterior parameter means and ranges for some key parameters, for example, the decomposition rate constant for the slow organic pool, the leaf mass per area, and nitrogen uptake flexibility. We conclude that changes in soil and crop management can trigger changes in key functions of the system, especially in the long-term, which are currently not considered by the model, for example, the composition and function of microbial populations in the soil. This means that we cannot assume that model parameter values will remain unchanged when the management of an agricultural system changes. It remains a challenge to include these kinds of feedback responses in soil-crop models in a sufficiently parsimonious way.

Funding

This work was supported by the Swedish Research Council for Sustainable Development, Formas [project No:2019–00518]. The field experiment was funded by the program for long-term field experiments at the Swedish University of Agricultural Sciences with financial support from the Swedish Board of Agriculture from 1993 to 2018.

CRediT authorship contribution statement

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

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.

Acknowledgment

We especially thank Professor Nicholas Jarvis (SLU) for constructive advice and valuable comments on the manuscript and for the language review. We also thank Professor Stefano Manzoni (Stockholm University) for valuable comments on the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.109856.

Data availability

Data will be made available on request.

References

Alderman, P.D., Stanfill, B., 2017. Quantifying model-structure- and parameter-driven uncertainties in spring wheat phenology prediction with Bayesian analysis. Eur. J. Agron. 88, 1–9. https://doi.org/10.1016/j.eja.2016.09.016.

Andersson, S., Bärring, L., Landelius, T., Samuelsson, P., Schimanke, S., 2021. SMHI Gridded Climatology (No. 03472116 (ISSN)), RMK, Rapport Meteorologi och Klimatologi.

Aronsson, H., Torstensson, G., 1998. Measured and simulated availability and leaching of nitrogen associated with frequent use of catch crops. Soil Use Manag 14, 6–13.

Beaudoin, N., Launay, M., Sauboua, E., Ponsardin, G., Mary, B., 2008. Evaluation of the soil crop model STICS over 8 years against the "on farm" database of Bruyères catchment. Eur. J. Agron. 29, 46–57. https://doi.org/10.1016/j.eja.2008.03.001.

Bergkvist, G., Öborn, I., 2011. Long. -Term. Field Exp. Swed. –what are they Des. Study what could they be Use For. Asp. Appl. Biol. 113, 75–85.

Bergström, L., Johnsson, H., 1988. Simulated nitrogen dynamics and nitrate leaching in a perennial grass ley. Plant Soil 105, 273–281.

Beven, K., 1993. Prophecy, reality and uncertainty in distributed hydrological modelling. Adv. Water Resour. 16, 41–51.

Beven, K., Binley, A., 1992. The future of distributed models: model calibration and uncertainty prediction. Hydrol. Process. 6, 279–298. https://doi.org/10.1002/hyp.3360060305.

Blombäck, K., Eckersten, H., Lewan, E., Aronsson, H., 2003. Simulations of soil carbon and nitrogen dynamics during seven years in a catch crop experiment. Agric. Syst. 76, 95–114. https://doi.org/10.1016/S0308-521X(02)00030-6.

Bregaglio, S., Willocquet, L., Kersebaum, K.C., Ferrise, R., Stella, T., Ferreira, T.B., Pavan, W., Asseng, S., Savary, S., 2021. Comparing process-based wheat growth models in their simulation of yield losses caused by plant diseases. Field Crops Res 265, 108108. https://doi.org/10.1016/j.fcr.2021.108108.

Brisson, N., Launay, M., Mary, B., Beaudoin, N., 2009. Conceptual basis, formalisations and parameterization of the STICS crop model. Editions Quae.

Brooks, R.H., Corey, A.T., 1964. Hydraulic properties of porous media. Hydrology paper No 3. Colorado State University.

Cabrera, M., Kissel, D., 1988. Evaluation of a method to predict nitrogen mineralized from soil organic matter under field conditions. Soil Sci. Soc. Am. J. 52, 1027–1031.

Cassman, K.G., Dobermann, A., Walters, D.T., 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. AMBIO J. Hum. Environ. 31, 132–140. https://doi.org/10.1579/0044-7447-31.2.132.

Constantin, J., Beaudoin, N., Launay, M., Duval, J., Mary, B., 2012. Long-term nitrogen dynamics in various catch crop scenarios: test and simulations with STICS model in a temperate climate. Agric. Ecosyst. Environ. 147, 36–46. https://doi.org/10.1016/j.agee.2011.06.006.

Constantin, J., Raynal, H., Casellas, E., Hoffmann, H., Bindi, M., Doro, L., Eckersten, H., Gaiser, T., Grosz, B., Haas, E., Kersebaum, K.-C., Klatt, S., Kuhnert, M., Lewan, E., Maharjan, G.R., Moriondo, M., Nendel, C., Roggero, P.P., Specka, X., Trombi, G., Villa, A., Wang, E., Weihermüller, L., Yeluripati, J., Zhao, Z., Ewert, F., Bergez, J.-E., 2019. Management and spatial resolution effects on yield and water balance at regional scale in crop models. Agric. For. Meteorol. 275, 184–195. https://doi.org/10.1016/j.agrformet.2019.05.013.

Coucheney, E., Eckersten, H., Hoffmann, H., Jansson, P.-E., Gaiser, T., Ewert, F., Lewan, E., 2018. Key functional soil types explain data aggregation effects on simulated yield, soil carbon, drainage and nitrogen leaching at a regional scale. Geoderma 318, 167–181. https://doi.org/10.1016/j.geoderma.2017.11.025.

Eriksson, J., Mattsson, L., Söderström, M., 2010. Tillståndet i svensk åkermark och gröda Data från 2001-2007 rapport 6349.

Frisk, M., Larsson, K., 1999. Agrarhistorisk landskapsanalys över Hallands län. Riksantikvarieämbetet.

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. https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2.

Hansson, A. -C., Pettersson, R., Paustian, K., 1987. Shoot and root production and nitrogen uptake in barley, with and without nitrogen fertilization. J. Agron. Crop Sci. 158, 163–171. https://doi.org/10.1111/j.1439-037X.1987.tb00258.x.

He, H., Jansson, P.-E., Gärdenäs, A.I., 2021. CoupModel (v6.0): an ecosystem model for coupled phosphorus, nitrogen, and carbon dynamics – evaluated against empirical data from a climatic and fertility gradient in Sweden. Geosci. Model Dev. 14, 735–761. https://doi.org/10.5194/gmd-14-735-2021.

He, J., Jones, J.W., Graham, W.D., Dukes, M.D., 2010. Influence of likelihood function choice for estimating crop model parameters using the generalized likelihood uncertainty estimation method. Agric. Syst. 103, 256–264. https://doi.org/10.1016/j.agsy.2010.01.006.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., 2018. ERA5 hourly data on single levels from 1979 to present, Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Hoffmann, H., Zhao, G., van Bussel, L., Enders, A., Specka, X., Sosa, C., Yeluripati, J., Tao, F., Constantin, J., Raynal, H., Teixeira, E., Grosz, B., Doro, L., Zhao, Z., Wang, E., Nendel, C., Kersebaum, K., Haas, E., Kiese, R., Klatt, S., Eckersten, H., Vanuytrecht, E., Kuhnert, M., Lewan, E., Rötter, R., Roggero, P., Wallach, D., Cammarano, D., Asseng, S., Krauss, G., Siebert, S., Gaiser, T., Ewert, F., 2015. Variability of effects of spatial climate data aggregation on regional yield simulation by crop models. Clim. Res. 65, 53–69. https://doi.org/10.3354/cr01326.

Hooghoudt, S., 1940. Contributions to knowledge of some natural properties of soil. VII. General consideration of the problem of local draining of soil, and of infiltration from parallel running drains and open drain furrows, ditches and drainage channels. Versl. Van. Landbouwkd. Onderz. 515, 707.

Janssens, I.A., Dieleman, W., Luyssaert, S., Subke, J.-A., Reichstein, M., Ceulemans, R., Ciais, P., Dolman, A.J., Grace, J., Matteucci, G., Papale, D., Piao, S.L., Schulze, E.-D., Tang, J., Law, B.E., 2010. Reduction of forest soil respiration in response to nitrogen deposition. Nat. Geosci. 3, 315–322. https://doi.org/10.1038/ngeo844.

Jansson, P., Karlberg, L., 2004. COUP manual: coupled heat and mass transfer model for soil-plant-atmosphere systems. Tech. Man. CoupModel 1, 453.

Jansson, P.-E., 2012. CoupModel: model use, calibration, and validation. Trans. ASABE 55, 1337–1346. https://doi.org/10.13031/2013.42245.

Johnson, A.D., Cabrera, M.L., McCracken, D.V., Radcliffe, D.E., 1999. LEACHN simulations of nitrogen dynamics and water drainage in an Ultisol. Agron. J. 91, 597–606.

Johnsson, H., 1991. The soil at Mellby experimental field. Intern. Rep. Div Water Manag. Swed. Univ. Agric. Sci. Uppsala.

Johnsson, H., Bergstrom, L., Jansson, P.-E., Paustian, K., 1987. Simulated nitrogen dynamics and losses in a layered agricultural soil. Agric. Ecosyst. Environ. 18, 333–356.

Johnsson, H., Jansson, P.-E., 1991. Water balance and soil moisture dynamics of field plots with barley and grass ley. J. Hydrol. 129, 149–173. https://doi.org/10.1016/0022-1694(91)90049-N.

Karlberg, L., Ben-Gal, A., Jansson, P.-E., Shani, U., 2006. Modelling transpiration and growth in salinity-stressed tomato under different climatic conditions. Ecol. Model. 190, 15–40. https://doi.org/10.1016/j.ecolmodel.2005.04.015.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N., Meinke, H., Hochman, Z., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.

Kersebaum, K.C., Hecker, J.-M., Mirschel, W., Wegehenkel, M., 2007. Modelling water and nutrient dynamics in soil–crop systems: a comparison of simulation models applied on common data sets. in: Modelling Water and Nutrient Dynamics in Soil–Crop Systems. Springer, pp. 1–17.

Knops, J.M., Reinhart, K., 2000. Specific leaf area along a nitrogen fertilization gradient. Am. Midl. Nat. 144, 265–272.

Kröbel, R., Smith, W., Grant, B., Desjardins, R., Campbell, C., Tremblay, N., Li, C., Zentner, R., McConkey, B., 2011. Development and evaluation of a new Canadian spring wheat sub-model for DNDC. Can. J. Soil Sci. 91, 503–520.

Kumar, U., Morel, J., Bergkvist, G., Palosuo, T., Gustavsson, A.-M., Peake, A., Brown, H., Ahmed, M., Parsons, D., 2021. Comparative analysis of phenology algorithms of the spring barley model in APSIM 7.9 and APSIM next generation: a case study for high latitudes. Plants 10, 443. https://doi.org/10.3390/plants10030443.

Lewan, E., 1993. Evaporation and discharge from arable land with cropped or bare soils during winter. Measurements and simulations. Agric. For. Meteorol. 64, 131–159. https://doi.org/10.1016/0168-1923(93)90026-E.

Lewan, E., 1994. Effects of a catch crop on leaching of nitrogen from a sandy soil: simulations and measurements. Plant Soil 166, 137–152. https://doi.org/10.1007/BF02185490.

Liang, Z., Cao, B., Jiao, Y., Liu, C., Li, X., Meng, X., Shi, J., Tian, X., 2022. Effect of the combined addition of mineral nitrogen and crop residue on soil respiration, organic carbon sequestration, and exogenous nitrogen in stable organic matter. Appl. Soil Ecol. 171, 104324. https://doi.org/10.1016/j.apsoil.2021.104324.
Monteith, J.L., 1965. Evaporation and environment. Presented at the Fogg, GE (éd) The State and Movement of Water in Living Organisms. th Symp. Soc. Exp. Biol, 19. Cambridge University Press, Cambridge, pp. 205–234.
Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., Van Cleemput, O., 1998. Closing the global N 2 O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutr. Cycl. Agroecosystems 52, 225–248.
Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12, 513–522. https://doi.org/10.1029/WR012i003p00513.
Nykänen, A., Salo, T., Granstedt, A., 2009. Simulated cereal nitrogen uptake and soil mineral nitrogen after clover-grass leys. Nutr. Cycl. Agroecosystems 85, 1–15. https://doi.org/10.1007/s10705-008-9244-5.
Nylinder, J., Stenberg, M., Jansson, P.-E., Klemedtsson, Å.K., Weslien, P., Klemedtsson, L., 2011. Modelling uncertainty for nitrate leaching and nitrous oxide emissions based on a Swedish field experiment with organic crop rotation. Agric. Ecosyst. Environ. 141, 167–183. https://doi.org/10.1016/j.agee.2011.02.027.
Salo, T.J., Palosuo, T., Kersebaum, K.C., Nendel, C., Angulo, C., Ewert, F., Bindi, M., Calanca, P., Klein, T., Moriondo, M., Ferrise, R., Olesen, J.E., Patil, R.H., Ruget, F., Takáč, J., Hlavinka, P., Trnka, M., Rötter, R.P., 2016. Comparing the performance of 11 crop simulation models in predicting yield response to nitrogen fertilization. J. Agric. Sci. 154, 1218–1240. https://doi.org/10.1017/S0021859615001124.
SCB, 2014. Drainage of agricultural land 2013, preliminary statistics. Örebro Stat. Sver. Off. Stat. Stat. Medd. JO 10 SM 1401 Swed.
Seidel, S.J., Palosuo, T., Thorburn, P., Wallach, D., 2018. Towards improved calibration of crop models – Where are we now and where should we go? Eur. J. Agron. 94, 25–35. https://doi.org/10.1016/j.eja.2018.01.006.
Spohn, M., Pötsch, E.M., Eichorst, S.A., Woebken, D., Wanek, W., Richter, A., 2016. Soil microbial carbon use efficiency and biomass turnover in a long-term fertilization experiment in a temperate grassland. Soil Biol. Biochem. 97, 168–175. https://doi.org/10.1016/j.soilbio.2016.03.008.
Springob, G., Kirchmann, H., 2002. C-rich sandy Ap horizons of specific historical land-use contain large fractions of refractory organic matter. Soil Biol. Biochem. 34, 1571–1581. https://doi.org/10.1016/S0038-0717(02)00127-X.
Springob, G., Kirchmann, H., 2010. Ratios of carbon to nitrogen quantify non-texture-stabilized organic carbon in sandy soils. J. Plant Nutr. Soil Sci. 173, 16–18. https://doi.org/10.1002/jpln.200900289.
Stenberg, M., Aronsson, H., Lindén, B., Rydberg, T., Gustafson, A., 1999. Soil mineral nitrogen and nitrate leaching losses in soil tillage systems combined with a catch crop. Soil Tillage Res 50, 115–125.
Stone, K.C., Hunt, P.G., Novak, J.M., Johnson, M.H., Watts, D.W., 2000. Flow-proportional, time-composited, and grab sample estimation of nitrogen export from an eastern coastal plain watershed. Trans. ASAE 43, 281–290. https://doi.org/10.13031/2013.2703.
Swedish Board of Agriculture, 2001. Riktlinjer för gödsling. Rapport 17.
Thomsen, I. k, Djurhuus, J., Christensen, B. t, 2003. Long continued applications of N fertilizer to cereals on sandy loam: grain and straw response to residual N. Soil Use Manag 19, 57–64. https://doi.org/10.1111/j.1475-2743.2003.tb00280.x.
Timsina, J., Humphreys, E., 2006. Performance of CERES-Rice and CERES-Wheat models in rice–wheat systems: A review. Agric. Syst. 90, 5–31. https://doi.org/10.1016/j.agsy.2005.11.007.
Torstensson, G., Aronsson, H., 2000. Nitrogen leaching and crop availability in manured catch crop systems in Sweden. Nutr. Cycl. Agroecosystems 56, 139–152.
Villa, A., Eckersten, H., Gaiser, T., Ahrends, H.E., Lewan, E., 2022. Aggregation of soil and climate input data can underestimate simulated biomass loss and nitrate leaching under climate change. Eur. J. Agron. 141, 126630.
Wallach, D., 2011. Crop model calibration: a statistical perspective. Agron. J. 103, 1144–1151. https://doi.org/10.2134/agronj2010.0432.
Wallach, D., Palosuo, T., Thorburn, P., Mielenz, H., Buis, S., Hochman, Z., Gourdain, E., Andrianasolo, F., Dumont, B., Ferrise, R., Gaiser, T., Garcia, C., Gayler, S., Harrison, M., Hiremath, S., Horan, H., Hoogenboom, G., Jansson, P.-E., Jing, Q., Justes, E., Kersebaum, K.-C., Launay, M., Lewan, E., Liu, K., Mequanint, F., Moriondo, M., Nendel, C., Padovan, G., Qian, B., Schütze, N., Seserman, D.-M., Shelia, V., Souissi, A., Specka, X., Srivastava, A.K., Trombi, G., Weber, T.K.D., Weihermüller, L., Wöhling, T., Seidel, S.J., 2023. Proposal and extensive test of a calibration protocol for crop phenology models. Agron. Sustain. Dev. 43, 46. https://doi.org/10.1007/s13593-023-00900-0.
Wu, L., McGechan, M., Lewis, D., Hooda, P., Vinten, A., 1998. Parameter selection and testing the soil nitrogen dynamics model SOILN. Soil Use Manag 14, 170–181.
Wu, M., Ran, Y., Jansson, P.-E., Chen, P., Tan, X., Zhang, W., 2019. Global parameters sensitivity analysis of modeling water, energy and carbon exchange of an arid agricultural ecosystem. Agric. For. Meteorol. 271, 295–306. https://doi.org/10.1016/j.agrformet.2019.03.007.
Yin, X., Kersebaum, K.-C., Beaudoin, N., Constantin, J., Chen, F., Louarn, G., Manevski, K., Hoffmann, M., Kollas, C., Armas-Herrera, C.M., Baby, S., Bindi, M., Dibari, C., Ferchaud, F., Ferrise, R., De Cortazar-Atauri, I.G., Launay, M., Mary, B., Moriondo, M., Öztürk, I., Ruget, F., Sharif, B., Wachter-Ripoche, D., Olesen, J.E., 2020b. Uncertainties in simulating N uptake, net N mineralization, soil mineral N and N leaching in European crop rotations using process-based models. Field Crops Res 255, 107863. https://doi.org/10.1016/j.fcr.2020.107863.
Yin, X., Beaudoin, N., Ferchaud, F., Mary, B., Strullu, L., Chlébowski, F., Clivot, H., Herre, C., Duval, J., Louarn, G., 2020a. Long-term modelling of soil N mineralization and N fate using STICS in a 34-year crop rotation experiment. Geoderma 357, 113956. https://doi.org/10.1016/j.geoderma.2019.113956.
Zang, H., Blagodatskaya, E., Wang, J., Xu, X., Kuzyakov, Y., 2017. Nitrogen fertilization increases rhizodeposit incorporation into microbial biomass and reduces soil organic matter losses. Biol. Fertil. Soils 53, 419–429. https://doi.org/10.1007/s00374-017-1194-0.

Table S.1. Crops grown and field management records.

Year	**Crop**	Sowing	Fertilization	Harvest day	Surface cultivation	Tillage
1984	Rapeseed	13-Apr	3-Apr	2-Sep	Missing info	Missing info
1985	Barley	6-May	22-Apr	26-Aug	26-Sep	18-Nov
1986	Oats	3-May	25-Apr	26-Aug	19-Sep	14-Nov
1987	Potatoes	10-May	8-May	8-Oct	-	20-Nov
1988	Barley	27-Apr	25-Apr	10-Aug	10-Sep	4-Nov
1989	Oats	20-Apr	19-Apr	18-Aug	7-Sep	19-Apr
1990	Wheat	9-Apr	7-Apr	24-Aug	13-Sep	6-Apr
1991	Barley	13-Apr	12-Apr	22-Aug	2-Sep	10-Apr
1992	Potatoes	21-May	20-May	10-Sep	16-Sep	15-May
1993	Barley	13-Apr	10-Apr	18-Aug	16-Sep	31-Mar
1994	Oats	21-Apr	20-Apr	9-Aug	5-Sep	8-Apr
1995	Rapeseed	27-Apr	26-Apr	24-Aug	14-Sep	12-Apr
1996	Wheat	27-Apr	25-Apr	5-Sep	19-Sep	18-Apr
1997	Barley	16-Apr	15-Apr	11-Aug	18-Sep	9-Apr
1998	Oats	22-Apr	22-Apr	8-Sep	16-Oct	21-Apr
1999	Wheat	24-Apr	23-Apr	1-Sep	15-Sep	14-Apr
2000	Barley	27-Apr	27-Apr	22-Aug	1-Sep	19-Apr
2001	Oats	4-May	3-May	30-Aug	2-Oct	20-Apr
2002	Potatoes	7-May	7-May	13-Sep	30-Sep	11-Apr
2003	Barley	15-Apr	4-Apr	11-Aug	18-Sep	1-Apr
2004	Rapeseed	14-Apr	7-Apr	3-Sep	16-Sep	2-Apr
2005	Triticale	11-Oct	19-Apr	24-Aug	14-Sep	-
2006	Oats	5-May	4-May	28-Aug	7-Sep	24-Apr
2007	Barley	15-Apr	13-Apr	4-Sep	20-Sep	10-Apr
2008	Wheat	29-Apr	24-Apr	4-Sep	-	16-Apr
2009	Oats	17-Apr	14-Apr	25-Aug	9-Sep	2-Apr
2010	Barley	23-Apr	22-Apr	3-Sep	-	14-Apr
2011	Wheat	3-May	3-May	9-Sep	12-Oct	12-Apr
2012	Oats	20-Apr	20-Apr	29-Aug	17-Sep	10-Apr
2013	Barley	3-May	30-Apr	27-Aug	-	18-Apr
2014	Wheat	29-Apr	28-Apr	22-Aug	11-Sep	21-Apr
2015	Oats	29-Apr	28-Apr	10-Sep	22-Sep	27-Apr
2016	Barley	13-Apr	12-Apr	24-Aug	1-Sep	6-Apr
2017	Wheat	11-Apr	6-Apr	15-Sep	26-Sep	29-Mar
2018	Oats	3-May	3-May	21-Aug	4-Aug	24-Apr
2019	Barley			26-Aug		

Table S.2. Equations in which the calibrated parameters are used.

Equation	**Definition**
Crop growth	
1. $C_{Leaf \to Grain} = a_{c,lg} \cdot C_{Leaf}$	Amount of C allocated to grain from leaf, analogous for C stem ($a_{C,sg}$), N leaf ($a_{N,lg}$) and N stem ($a_{N,sg}$) to grain
2. $f(CN_{leaf}) = \begin{cases} 1 & CN_{\text{leaf}} < p_{\text{CNOpt}} \\ 1 + \frac{CN_{\text{leaf}} - p_{CN,Opt}}{p_{CN,\text{ Opt}}\, p_{CN,Th}} & p_{CN,Opt} \leq CN_{\text{leaf}} \leq p_{CNTh} \\ 0 & CN_{\text{leaf}} > p_{\text{CNTh}} \end{cases}$	The leaf nitrogen response
3. $g_l = \frac{R_{is}}{R_{is}+g_{ris}} \frac{g_{\max}}{1+\frac{(e_s - e_a)}{g_{vpd}}}$	Lohammar equation (calculation used for leaf conductance)
4. $E_{\text{ta}} = E_{\text{ta}}{}^* + f_{\text{umov}} \cdot (E_{tp}{}^* - E_{ta}{}^*)$	Actual transpiration is calculated in two steps to account for possible compensatory uptake of water by roots in layers with no water stress if there are roots in other layers that are exposed to water stress.
5. $f_{\text{leaf}} = l_{c1}$	The C allocation fraction to the leaves
6. $C_{Atm \to a} = \varepsilon_L f(T_{\text{Air}}) f(CN_{\text{leaf}}) f(E_{ta}/E_{pp}) R_{s,pl}$	Leaf assimilation
7. $N_{\text{Demand 2}} = (N_{\text{Demand}} - N_{\text{TotUpt}}) n_{\text{Uptflex}}$	Compensatory uptake due to the flexibility of roots
8. $A_l = \frac{B_l}{p_{lsp}}$	Leaf area index
Litter and respiration	
9. $C_{\text{Decomp}} = k_h f(T) f(\theta) C_{\text{Humus}}$	Decomposition rate of the slow (humus) pool
10. $C_{\text{Litter} \to \text{Humus}} = f_{e,l} f_{h,l} C_{\text{Decomp}}$ $C_{\text{Litter} \to \text{Litter}} = f_{e,l}(1 - f_{h,l}) \cdot C_{\text{Decomp}}$	Litter and humus formed from litter decomposition
Soil and water	
11. 1. $\theta = \theta_s$ $f(\theta) = p_{\theta \text{ satact}}$ 2. $\theta_{\text{wilt}} < \theta < \theta_s$ $f(\theta) = \min\left(\left(\frac{\theta_s - \theta}{p_{\theta Upp}}\right)^{p_{\theta p}} (1 - p_{\theta \text{ satact}}) + p_{\theta \text{ satact}}, \left(\frac{\theta - \theta_{\text{wilt}}}{p_{\theta \text{ Low}}}\right)^{p_{\theta p}}\right)$ 3.	Soil moisture response function for microbial activity, mineralisation-immobilisation, nitrification and denitrification.

$\theta < \theta_{\text{wilt}}$ $f(\theta) = 0$	
12. $f_\psi(z) = \min\left(\left(\frac{\psi_c}{\psi(z)}\right)^{p_1 E_{tp} + p_2}, f_\theta\right)$	Water potential response function in the dry range
13. $q_{\text{deep}} = \frac{8k_{\text{sat}}\left(z_{sat} - z_{p2}\right)^2}{d_{p2}{}^2}$	Bottom boundary seepage equation

S.3. Initial soil organic C and N

Upper depth (cm)	Lower depth (cm)	Total SOC ($g\ m^{-2}$)	Total SON ($g\ m^{-2}$)	Inert SOC ($g\ m^{-2}$)	Inert SON ($g\ m^{-2}$)	Slow Pool SOC ($g\ m^{-2}$)	Slow pool SON ($g\ m^{-2}$)
0	0.05	2259.1	117.5	1518.4	43.4	740.7	74.1
0.05	0.15	4518.2	234.9	3036.9	86.8	1481.3	148.1
0.15	0.3	6777.3	352.4	4555.3	130.2	2222.0	222.2
0.3	0.45	1718.1	67.6	1459.0	41.7	259.1	25.9
0.45	0.6	1209.9	47.6	1027.4	29.4	182.5	18.2
0.6	0.75	1057.7	43.8	868.1	24.8	189.7	19.0
0.75	0.9	334.3	13.8	274.3	7.8	59.9	6.0
0.9	1.1	1.02E-03	1.02E-04	1.40E-06	4.00E-08	1.02E-03	1.02E-04
1.1	1.4	1.02E-03	1.02E-04	1.40E-06	4.00E-08	1.02E-03	1.02E-04
1.4	1.7	1.02E-03	1.02E-04	1.40E-06	4.00E-08	1.02E-03	1.02E-04
1.7	2	1.02E-03	1.02E-04	1.40E-06	4.00E-08	1.02E-03	1.02E-04
2	2.3	1.02E-03	1.02E-04	1.40E-06	4.00E-08	1.02E-03	1.02E-04

S.4. List of symbols

θ	Actual soil moisture content	(vol %)
ψ_c	Critical pressure head for reduction of potential water uptake	(cm water)
θ_s	Soil moisture content at saturation	(vol %)
θ_{wilt}	*Soil moisture content at wilting point*	(vol %)
ψ_z	Soil water potential	(cm water)
$a_{c,lg}$	Fraction of carbon in leaves reallocated to grains during grain development	(-)
A_l	Leaf area index	(-)
B_l	total mass of leaf (carbon content)	($g\ cm^{-2}$)
$C_{Atm \to a}$	Total plant growth	($g\ cm^{-2}$)
C_{leaf}	C content in leaf	($g\ m^{-2}$)
CN_{leaf}	C-N ratio in leaf	(-)
d_{p2}	Distance between assumed drainage system for calculation of deep percolation	(m)

e_a	Actual vapor pressure	(Pa)
e_s	Vapor pressure at saturation	(Pa)
E_{ta}	Actual transpiration	(mm day^{-1})
E_{ta}^*	Uptake without any account for compensatory uptake	(mm day^{-1})
E_{tp}	Potential transpiration rate	(mm day^{-1})
E_{tp}^*	Potential transpiration with eventual reduction due to interception evaporation	(mm day^{-1})
$f(\theta)$	Common response function for soil moisture	(-)
$f(CN_{leaf})$	Leaf nitrogen response	(-)
$f(E_{ta}/E_{tp})$	Water reduction function	(-)
$f(T)$	Common response function for temperature	(-)
$f(T_a)$	Air temperature response	(-)
$f_{e,l}$	Efficiency of the decay of litter	(day^{-1})
$f_{h,l}$	Fraction of C and N in the litter pool that will enter the humus pool	(day^{-1})
f_{leaf}	The allocation fraction to the leaves	(-)
f_{umov}	Degree of compensation in the actual transpiration	(-)
gl	Leaf conductance	(m s^{-1})
g_{max}	The maximal conductance of fully open stomata	(m s^{-1})
g_{ris}	Global radiation intensity that represents half-light saturation in the light response	(J m^{-2} day^{-1})
g_{vpd}	Vapor pressure deficit that corresponds to a 50 % reduction of stomata conductance	(Pa)
K_h	Rate coefficient for the decay of humus (slow pool)	(day^{-1})
K_{sat}	Conductivity of the lowest layer	(mm day^{-1})
l_{c1}	Fraction of the mobile carbon assimilates allocated to the new shoots	(-)
N_{Demand}	The plant root uptake demand of nitrogen	(g N m^{-2})
N_{TotUpt}	Total mineral nitrogen uptake	(g N m^{-2})
$n_{Uptflex}$	Flexibility degree of the roots	(-)
$P_{\theta Low}$	Lower limit of the Water content interval in soil moisture response function	(vol %)
$P_{\theta p}$	Coefficient in the soil moisture response function	(-)
$p_{\theta satact}$	Saturation activity in soil moisture response function	(vol %)
$P_{\theta Upp}$	Upper limit of the *water content interval in soil moisture response function*	(vol %)
P_1	Coefficient for the dependence of potential water uptake in moisture reduction function	(day^{-1})
P_2	Coefficient in moisture reduction function	(kg m^{-2} day^{-1})
$P_{CN,Opt}$	Optimum C-N ratio in leaves for photosynthesis	(-)
$P_{CN,Th}$	Threshold C-N ratio in leaves. Above this value no photosynthesis occurs	(-)
$P_{l,sp}$	Leaf mass per area	(g C m^{-2})
R_{is}	Global radiation	(J m^{-2} day^{-1})
$R_{s,pl}$	Global radiation absorbed by canopy	(J m^{-2} day^{-1})
Z_{p2}	Depth for assumed drainage level for calculation of deep percolation	(m)
Z_{sat}	Simulated depth of the ground water table	(m)
ε_L	Radiation use efficiency for photosynthesis at optimum temperature, moisture and C-N ratio	(g Dw MJ^{-1})

II

Agriculture, Ecosystems and Environment 397 (2026) 110090

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

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

David Nimblad Svensson [*], Helena Aronsson, Lisbet Norberg, Elisabet Lewan

Department of Soil and Environment, Swedish University of Agricultural Sciences, Box 7014, 750 07 Uppsala, Sweden

ARTICLE INFO

Keywords:
NAO
Trend analysis
Long-term experiment
Soil nitrate
Crop yield
Sandy soil

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

* Corresponding author.
E-mail address: david.nimblad.svensson@slu.se (D. Nimblad Svensson).

https://doi.org/10.1016/j.agee.2025.110090
Received 2 May 2025; Received in revised form 7 November 2025; Accepted 11 November 2025
Available online 15 November 2025

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

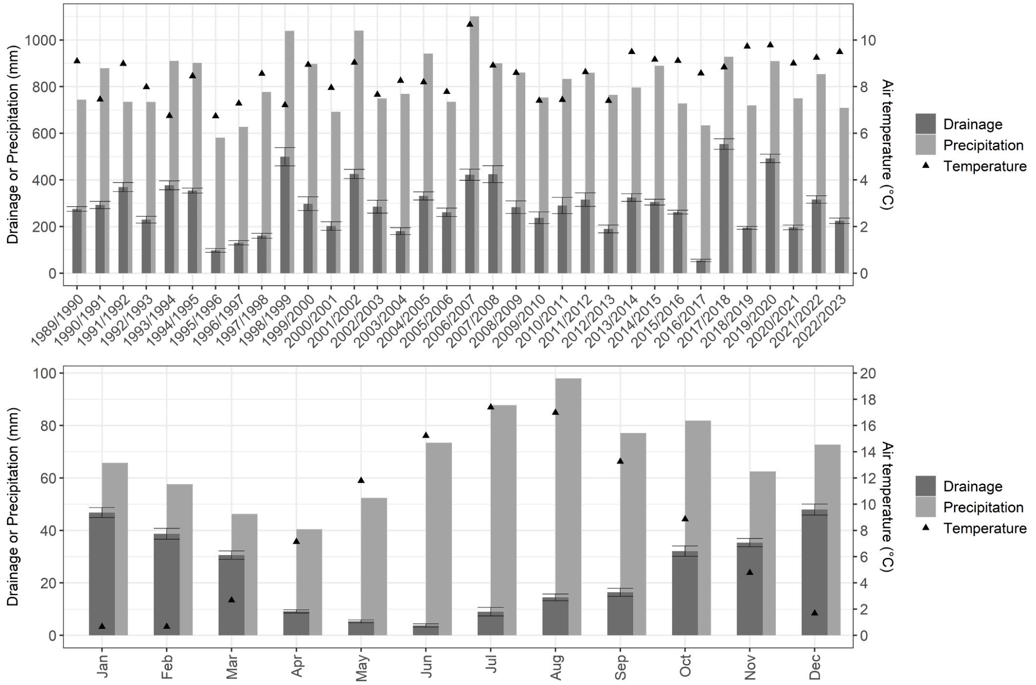

Fig. 1. Mean annual (A) and monthly (B) precipitation (mm), air temperature (°C) and discharge (mm) for the 8 plots over the years 1989–2023. Bars show standard error for the 8 plots.

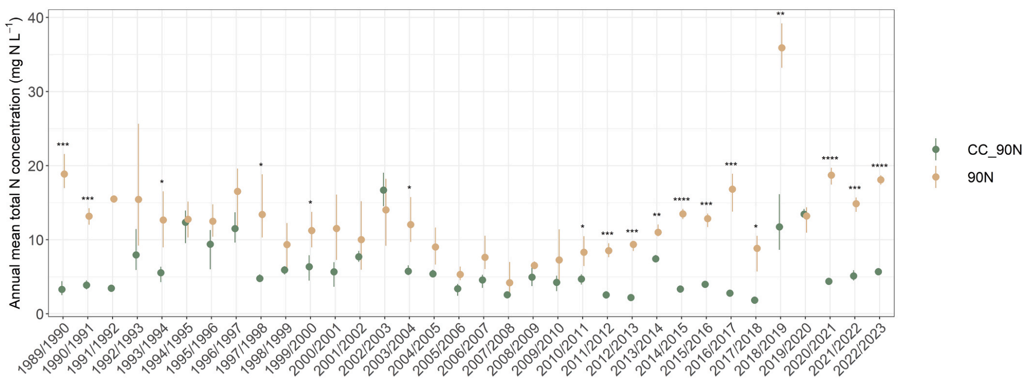

Fig. 2. Annual mean concentration (mg L^{-1}) of total nitrogen (N) for treatments with fertilization and with and without cover crops (CC_90N and 90N, n = 3). Stars represent significant differences between treatments (*=$p < 0.05$, **=$p < 0.01$, ***=$p < 0.001$, ****=$p < 0.0001$).

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,

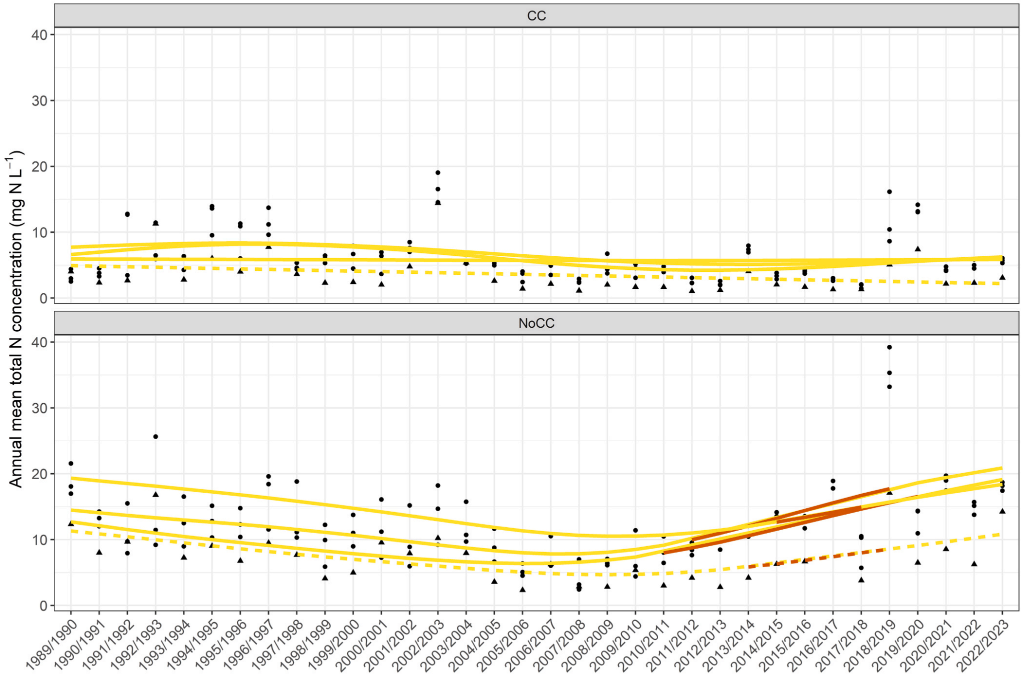

Fig. 3. Generalized additive model (GAM) fit to total nitrogen (N) concentration (mg L^{-1}) in drainage water for field plots with cover crop (CC, top panel) and without cover crop (NoCC, bottom panel), one line per replicate. The dashed lines and triangles represent the unfertilized treatments. Red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

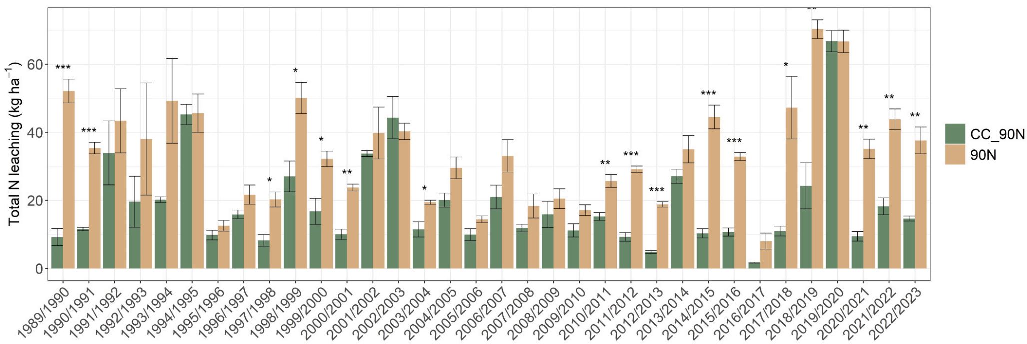

Fig. 4. Mean annual total nitrogen (N) leaching (kg ha^{-1}) for treatments with and without an under-sown cover crop (CC_90N and 90N, n = 3). Stars represent significant differences between treatments (*=p < 0.05, **=p < 0.01, ***=p < 0.001).

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

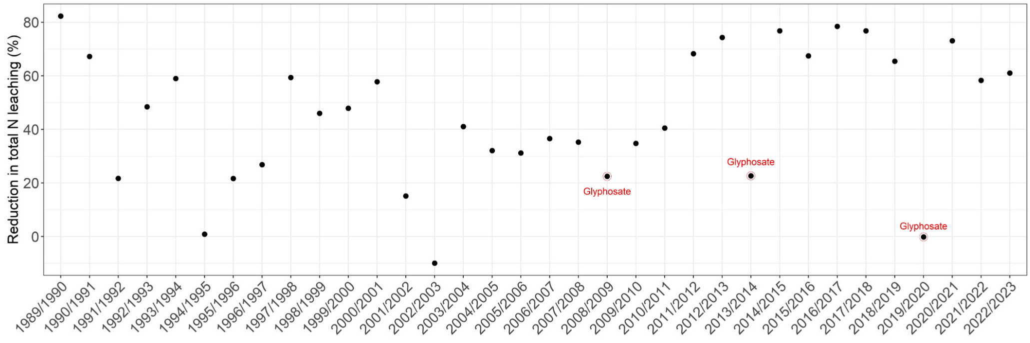

Fig. 5. Reduction in annual nitrogen (N) leaching in the treatment with cover crop (CC_90N) compared to that without a cover crop (90N).

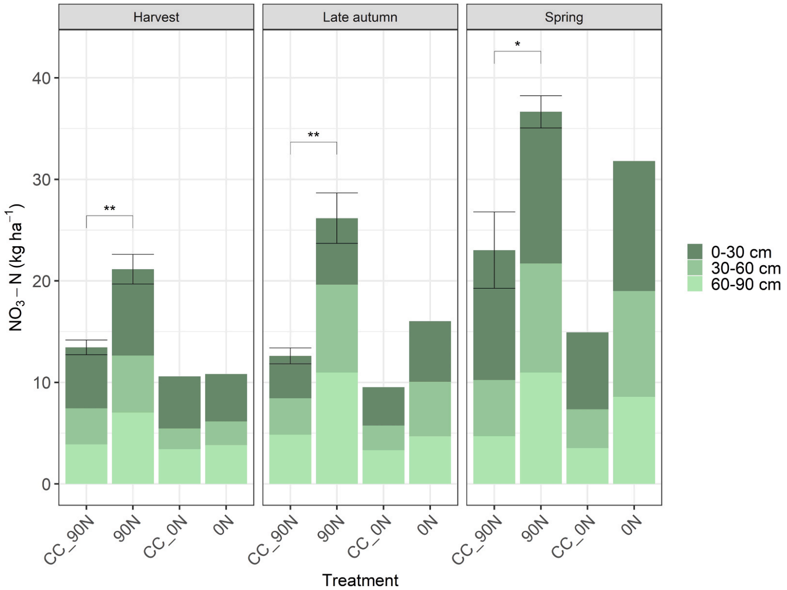

Fig. 6. Mean soil nitrate nitrogen (NO_3-N, kg ha^{-1}) in treatments with and without an under-sown cover crop and fertilization (n = 3 for CC_90N and 90N, n = 1 for CC_0N and 0N). Samples were taken at three sampling periods (at harvest, in late autumn and spring) over 34 years, at three soil depths (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 (ρ=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 (ρ=-0.48, $P < 0.05$) and positively correlated with N leaching in both 90N (ρ=0.35, $P < 0.05$) and CC_90N (ρ=0.42, $P < 0.05$). Positive correlations were found between annual mean NAO_i and soil NO_3-N content in late autumn (ρ=0.44, $P < 0.05$) and annual N leaching (ρ=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 (ρ=0.48, $P < 0.05$) and negatively correlated to spring soil NO_3-N content (ρ=-0.38, $P < 0.05$)

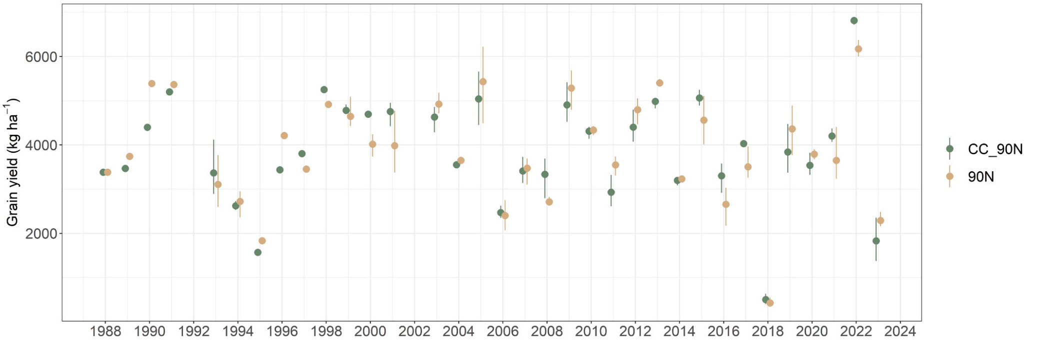

Fig. 7. Grain yield (kg ha^{-1}) for cereal crops in treatments with (CC_90N) and without (90N) cover crop. Years with potatoes were excluded. Dots represent the mean and the lines indicate min/max values of the three replicates.

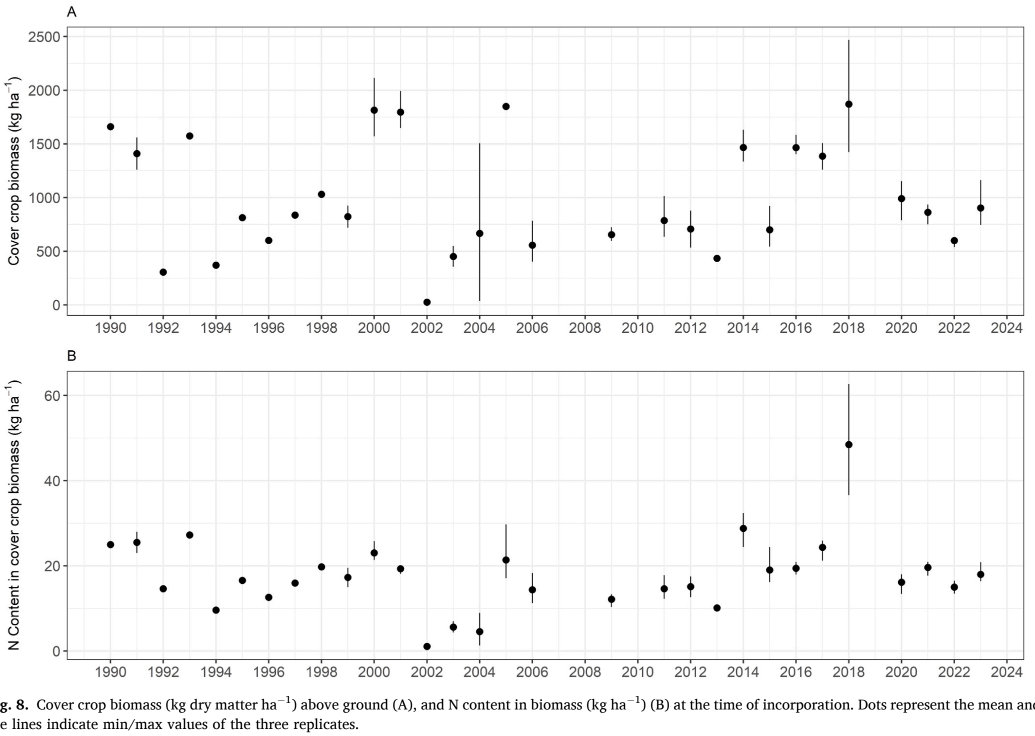

Fig. 8. Cover crop biomass (kg dry matter ha^{-1}) above ground (A), and N content in biomass (kg ha^{-1}) (B) at the time of incorporation. Dots represent the mean and the lines indicate min/max values of the three replicates.

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 (ρ=0.53, $P < 0.05$) and N content in CC biomass in CC_90N (ρ=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

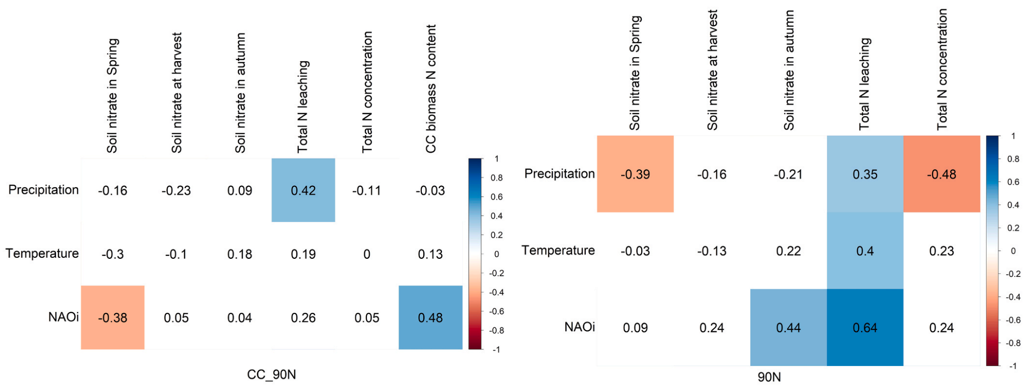

Fig. 9. Spearman rank correlation coefficients (ρ) for relationships between nitrogen (N) variables and weather variables for the treatments with and without cover crop, CC_90N (left) and 90N (right). Significant correlations ($P < 0.05$, $n = 34$) are highlighted in red (negative) or in blue (positive). 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.

Funding

This work was supported by the Swedish Research Council for Sustainable Development, Formas [project No: 2019–00518]. The field experiment was funded by the program for long-term field experiments at the Swedish University of Agricultural Sciences with financial support from the Swedish Board of Agriculture from 1993 to 2018.

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.

Acknowledgment

We especially thank Professor Nicholas Jarvis (SLU) for constructive advice and valuable comments on the manuscript and for the language review. We thank Claudia von Brömssen (SLU) for statistical advice and Professor Erik Kjellström (SMHI) and Professor Stefano Manzoni (Stockholm University) for valuable comments on the manuscript. We also wish to thank Maria Blomberg for technical assistance, the Water Laboratory at the Department of Aquatic Sciences and Assessment, the

Soil and Plant laboratory at the Department of Soil and Environment (all SLU), and the staff at the Rural Economy and Agricultural Society in Halland.

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.

References

Alonso-Ayuso, M., Gabriel, J.L., Quemada, M., 2014. The kill date as a management tool for cover cropping success. PLoS ONE 9, e109587. https://doi.org/10.1371/journal.pone.0109587.

Andersen, M.S., Engedal, T., Bruun, S., Jensen, L.S., Hansen, V., 2025. Emissions of N2O following field incorporation of leguminous and non-leguminous cover crops. Agric. Ecosyst. Environ. 379, 109335. https://doi.org/10.1016/j.agee.2024.109335.

Andersson, S., Bärring, L., Landelius, T., Samuelsson, P., Schimanke, S., 2021. SMHI gridded climatology (No. 03472116 (ISSN). RMK Rapp. Meteorol. och Klimatol.

Aronsson, H., Hansen, E.M., Thomsen, I.K., Liu, J., Ogaard, A.F., Kankanen, H., Ulen, B., 2016. The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. J. Soil Water Conserv 71, 41–55. https://doi.org/10.2489/jswc.71.1.41.

Bergkvist, G., Öborn, I., 2011. Long-term field experiments in Sweden–what are they designed to study and what could they be used for. Asp. Appl. Biol. 113, 75–85.

Böldt, M., Taube, F., Vogeler, I., Reinsch, T., Kluß, C., Loges, R., 2021. Evaluating different catch crop strategies for closing the nitrogen cycle in cropping systems—field experiments and modelling. Sustainability 13, 394. https://doi.org/10.3390/su13010394.

Chen, D., Hellström, C., 2002. The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations. Tellus A 51, 505–516. https://doi.org/10.1034/j.1600-0870.1999.t01-4-00004.x.

R. Core Team, 2024. R: A Language and Environment for Statistical Computing.

Grant, R., Nielsen, K., Waagepetersen, J., 2006. Reducing nitrogen loading of inland and marine waters—evaluation of danish policy measures to reduce nitrogen loss from farmland. AMBIO J. Hum. Environ. 35, 117–123. https://doi.org/10.1579/0044-7447(2006)35[117:RNLOIA]2.0.CO;2.

Hansson, K., Ejhed, H., Widén-Nilsson, E., Johnsson, H., Tengdelius Brunell, J., Gustavsson, H., Hytteborn, J., Åkerblom, S., 2019. Näringsbelastningen på Östersjön och Västerhavet 2017: Sveriges underlag till HELCOM:s sjunde pollution load compilation (No. 978-91-88727-53- 4 (ISBN). Havs och Vatten Rapp. Havs och Vatten Göteborg.

Jarvis, S., Hutchings, N., Brentrup, F., Olesen, J.E., van de Hoek, K.W., 2011. Nitrogen flows in farming systems across Europe. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment. Cambridge University Press, Cambridge, pp. 211–228. https://doi.org/10.1017/CBO9780511976988.013.

Johansson, B., Chen, D., 2003. The influence of wind and topography on precipitation distribution in Sweden: statistical analysis and modelling. Int. J. Clim. 23, 1523–1535. https://doi.org/10.1002/joc.951.

Johnsson, H., 1991. The soil at Mellby experimental field. Intern. Rep. Div. Water Manag. Swed. Univ. Agric. Sci. Upps.

Klages, S., Heidecke, C., Osterburg, B., 2020. The impact of agricultural production and policy on water quality during the dry year 2018, a case study from Germany. Water 12, 1519. https://doi.org/10.3390/w12061519.

Kumar, U., Thomsen, I.K., Vogeler, I., Mäenpää, M., Hansen, E.M., 2025. Residual effects of repeated catch crops on spring barley yield and nitrate leaching. Field Crops Res. 327, 109911. https://doi.org/10.1016/j.fcr.2025.109911.

Kyllmar, K., Bechmann, M., Blicher-Mathiesen, G., Fischer, F.K., Fölster, J., Iital, A., Lagzdiņš, A., Povilaitis, A., Rankinen, K., 2023. Nitrogen and phosphorus losses in Nordic and Baltic agricultural monitoring catchments – Spatial and temporal variations in relation to natural conditions and mitigation programmes. CATENA 230, 107205. https://doi.org/10.1016/j.catena.2023.107205.

Leip, A., Billen, G., Garnier, J., Grizzetti, B., Lassaletta, L., Reis, S., Simpson, D., Sutton, M.A., de Vries, W., Weiss, F., Westhoek, H., 2015. Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. Environ. Res. Lett. 10, 115004. https://doi.org/10.1088/1748-9326/10/11/115004.

Lewan, E., 1994. Effects of a catch crop on leaching of nitrogen from a sandy soil: Simulations and measurements. Plant Soil 166, 137–152. https://doi.org/10.1007/BF02185490.

Li, X., Petersen, S.O., Sørensen, P., Olesen, J.E., 2015. Effects of contrasting catch crops on nitrogen availability and nitrous oxide emissions in an organic cropping system. Agric. Ecosyst. Environ. 199, 382–393. https://doi.org/10.1016/j.agee.2014.10.016.

Manzoni, S., Schimel, J.P., Porporato, A., 2012. Responses of soil microbial communities to water stress: results from a meta-analysis. Ecology 93, 930–938. https://doi.org/10.1890/11-0026.1.

Mellander, P.-E., Jordan, P., Bechmann, M., Fovet, O., Shore, M.M., McDonald, N.T., Gascuel-Odoux, C., 2018. Integrated climate-chemical indicators of diffuse pollution from land to water. Sci. Rep. 8, 944. https://doi.org/10.1038/s41598-018-19143-1.

Meyer, N., Bergez, J.-E., Constantin, J., Justes, E., 2019. Cover crops reduce water drainage in temperate climates: A meta-analysis. Agron. Sustain. Dev. 39, 3. https://doi.org/10.1007/s13593-018-0546-y.

Nasser, V., Dechow, R., Helfrich, M., Meijide, A., Rummel, P.S., Koch, H.-J., Ruser, R., Essich, L., Dittert, K., 2024. Managing Soil Nitrogen Surplus: The Role of Winter Cover Crops in N_2 O Emissions and Carbon Sequestration. https://doi.org/10.5194/egusphere-2024-2849.

Nimblad Svensson, D., Aronsson, H., Jansson, P.-E., Lewan, E., 2025. Insights gained from modeling grain yield, nitrate leaching, and soil nitrogen dynamics in a long-term field experiment with spring cereals on fertilized and unfertilized soil over 35 years. Field Crops Res. 326, 109856. https://doi.org/10.1016/j.fcr.2025.109856.

Norberg, L., Aronsson, H., 2020. Effects of cover crops sown in autumn on N and P leaching. Soil Use Manag. 36, 200–211. https://doi.org/10.1111/sum.12565.

Norberg, L., Aronsson, H., 2024. Effects of spring and autumn tillage, catch crops, and pig manure application on long-term nutrient leaching from a loamy sand. Eur. J. Agron. 156, 127156. https://doi.org/10.1016/j.eja.2024.127156.

Øygarden, L., Deelstra, J., Lagzdins, A., Bechmann, M., Greipsland, I., Kyllmar, K., Povilaitis, A., Iital, A., 2014. Climate change and the potential effects on runoff and nitrogen losses in the Nordic–Baltic region. Agric. Ecosyst. Environ. 198, 114–126. https://doi.org/10.1016/j.agee.2014.06.025.

Stenberg, M., Aronsson, H., Lindén, B., Rydberg, T., Gustafson, A., 1999. Soil mineral nitrogen and nitrate leaching losses in soil tillage systems combined with a catch crop. Soil Tillage Res. 50, 115–125.

Sutton, M.A., Billen, G., Bleeker, A., Erisman, J.W., Grennfelt, P., van Grinsven, H., Grizzetti, B., Howard, C.M., Leip, A., 2011. Technical summary. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511976988.003.

Thomsen, I.K., Christensen, B.T., 1999. Nitrogen conserving potential of successive ryegrass catch crops in continuous spring barley. Soil Use Manag 15, 195–200. https://doi.org/10.1111/j.1475-2743.1999.tb00088.x.

Thomsen, I.K., Hansen, E.M., 2014. Cover crop growth and impact on N leaching as affected by pre- and postharvest sowing and time of incorporation. Soil Use Manag 30, 48–57. https://doi.org/10.1111/sum.12083.

Thomsen, I.K., Lægdsmand, M., Olesen, J.E., 2010. Crop growth and nitrogen turnover under increased temperatures and low autumn and winter light intensity. Agric. Ecosyst. Environ. 139, 187–194. https://doi.org/10.1016/j.agee.2010.07.019.

Thorup-Kristensen, K., Dresbøll, D.B., 2010. Incorporation time of nitrogen catch crops influences the N effect for the succeeding crop: N effect of catch crop incorporation time. Soil Use Manag 26, 27–35. https://doi.org/10.1111/j.1475-2743.2009.00255.x.

Thorup-Kristensen, K., Magid, J., Jensen, L.S., 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. in: Advances in Agronomy. Elsevier, pp. 227–302. https://doi.org/10.1016/S0065-2113(02)79005-6.

Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112, 58–72. https://doi.org/10.1016/j.agee.2005.07.003.

Ulén, B., Lewan, E., Kyllmar, K., Blomberg, M., Andersson, S., 2019. Impact of the North Atlantic oscillation on Swedish winter climate and nutrient leaching. J. Environ. Qual. 48, 941–949. https://doi.org/10.2134/jeq2018.06.0237.

Valkama, E., Lemola, R., Känkänen, H., Turtola, E., 2015. Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries. Agric. Ecosyst. Environ. 203, 93–101. https://doi.org/10.1016/j.agee.2015.01.023.

Van Schöll, L., Van Dam, A., Leffelaar, P., 1997. Mineralisation of nitrogen from an incorporated catch crop at low temperatures: experiment and simulation. Plant Soil 188, 211–219.

Von Brömssen, C., Betnér, S., Fölster, J., Eklöf, K., 2021. A toolbox for visualizing trends in large-scale environmental data. Environ. Model. Softw. 136, 104949. https://doi.org/10.1016/j.envsoft.2020.104949.

Table S1. Main crops grown in the field experiment.

Year	**Main Crop**
1989	Oats
1990	Wheat
1991	Barley
1992	Potatoes/Oats*
1993	Barley
1994	Oats
1995	Rapeseed
1996	Wheat
1997	Barley
1998	Oats
1999	Wheat
2000	Barley
2001	Oats
2002	Potatoes
2003	Barley
2004	Rapeseed
2005	Triticale
2006	Oats
2007	Barley
2008	Wheat
2009	Oats
2010	Barley
2011	Wheat
2012	Oats
2013	Barley
2014	Wheat
2015	Oats
2016	Barley
2017	Wheat
2018	Oats
2019	Barley
2020	Wheat
2021	Oats
2022	Barley
2023	Wheat

* Potatoes in plot 2, 5, 7, 10 and Oats in plot 11-14

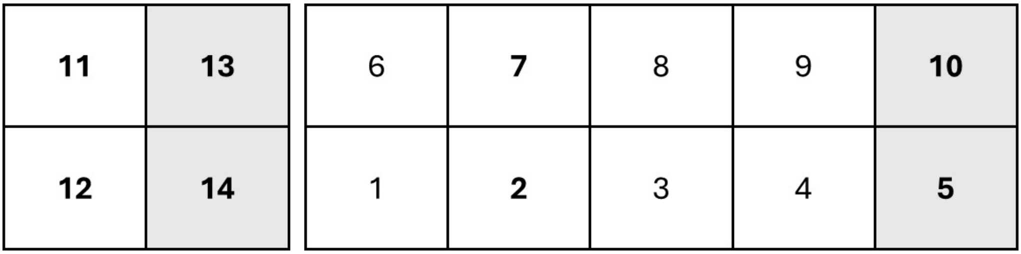

Figure S1. Location of the field plots in the experiment. 90N consisted of plot 2, 11, 12; CC_90N of plot 10, 13, 14; 0N of plot 7 and CC_0N of plot 5 (Grey shading indicates plots with cover crops).

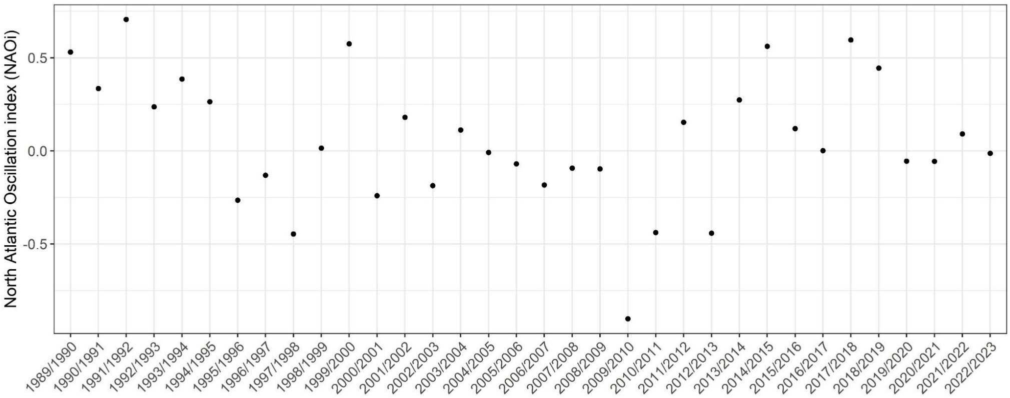

Figure S2. The North Atlantic Oscillation index (NAOi) based on agrohydrological years (1st July-31st June).

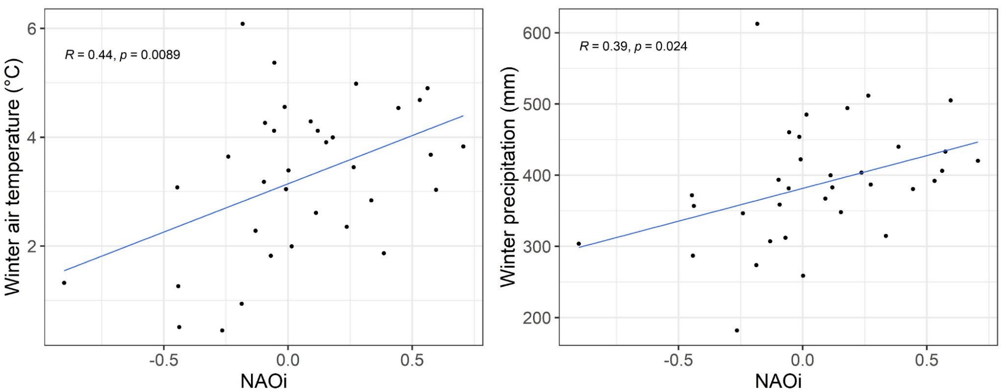

Figure S3. Correlation between the North Atlantic Oscillation index (NAOi) based on agrohydrological years (1st July-31st June) and winter air temperature (left) and precipitation (right) (1st October-31st March).

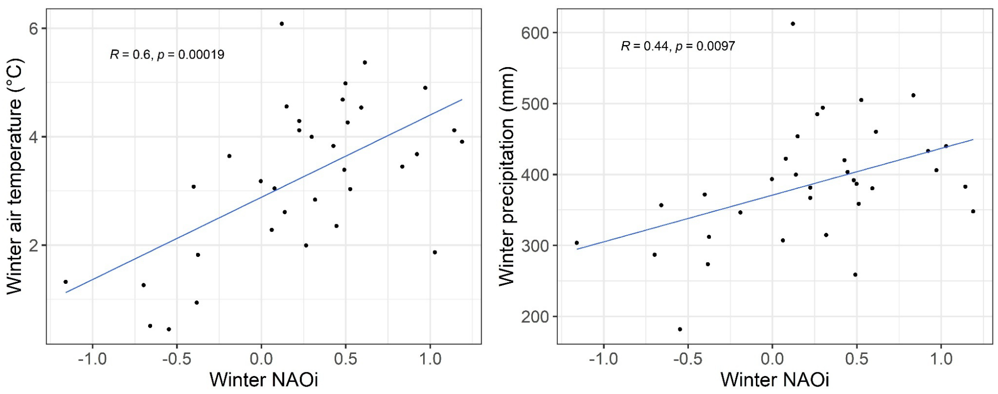

Figure S4. Correlation between the winter North Atlantic Oscillation index (NAOi) and winter air temperature (left) and precipitation (right) (1st October-31st March).

Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2026:13

This thesis explored the impacts of under-sown perennial ryegrass cover crops on nitrogen dynamics in spring cereals in south-west Sweden under current and future climate conditions. The work combined soil–vegetation modelling, climate scenarios and statistical analysis of data from an ongoing long-term field experiment. Cover crops consistently reduced N leaching without yield loss, increased soil organic nitrogen, and mitigated increases in N mineralisation under warmer climates. Model projections (2020–2100) showed increasing cover crop efficiency, especially under high-emission scenarios.

David Nimblad Svensson received his graduate education at the Department of Soil and Environment, SLU, Uppsala. He holds an MSc degree in Soil Sciences from SLU, Uppsala.

Acta Universitatis Agriculturae Sueciae presents doctoral theses from the Swedish University of Agricultural Sciences (SLU).

SLU generates knowledge for the sustainable use of biological natural resources. Research, education, extension, as well as environmental monitoring and assessment are used to achieve this goal.

ISSN 1652-6880
ISBN (print version) 978-91-8124-210-2
ISBN (electronic version) 978-91-8124-230-0