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The environmental trade-off of fertiliser, residue and catch crop management in Danish cropping systems

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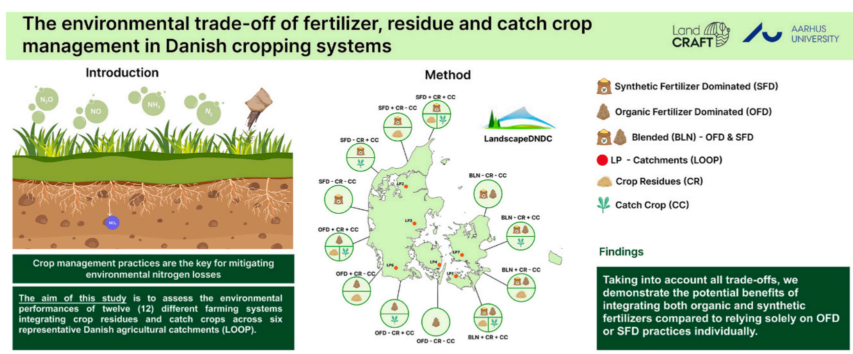
HIGHLIGHTS

- Combining manure with synthetic fertilisers reduces nitrogen emissions and enhances soil carbon sequestration.
- Incorporating crop residue and catch crops increases nitrogen use efficiency and improves the soil net GHG balance.
- Targeted management of fertilisers, residues, and catch crops can enhance the sustainability of crop production systems.
- Efficient nitrogen fertiliser distribution and management are vital for reducing nitrogen-related environmental impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Nitrogen is an essential macronutrient in agriculture, affecting both crop yields and soil health. In Denmark, one of the most densely farmed regions in the world, excess reactive nitrogen (Nr) compounds are lost to the environment along gaseous and hydrological pathways in forms such as nitrate, ammonia, nitrogen oxides and dinitrogen.

Objectives: Here, we aim to assess the effect of different field management practices (fertilisation, crop residue management or cultivation of catch crops) on environmental Nr losses and the field scale soil net GHG balance (i.e., sum of soil C stock changes and direct and indirect N_2O emissions).

Methods: For this purpose, highly detailed data from the Danish Agricultural Watershed Monitoring Program (LOOP-program; 2013–2019) were used in combination with the process-based model LandscapeDNDC.

Results and conclusions: The results indicate that a mixture of organic and synthetic fertilisers turns soils to a stronger net sink of GHGs (~70 – ~514 $kgCO_2$-eq ha^{-1} yr^{-1}) compared to exclusive use of only one type of fertiliser. In addition, incorporating crop residue and cultivation of catch crops increases the nitrogen use efficiency (NUE) by 3–11 % on average and decreases environmental Nr losses.

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Significance: These findings emphasize the potential of targeted fertiliser, residue and catch crop management to increase the sustainability of crop production systems in Denmark.

1. Introduction

As the most widely used nutrient required by plants, Nitrogen (N) is critical for crop growth. However, excessive N fertilisation can lead to pollution of aquatic, marine, terrestrial, and atmospheric environments (Braun, 2007). Nitrogen pollution imposes a significant economic burden on the European Union, with estimates ranging from €70 billion to €320 billion per year (Directorate-General for Environment, 2022). In Denmark, a heavily farmed region with more than 60 % of its land devoted to agriculture (FAO, 2014), excess nitrogen from farming practices is released to the environment in reactive forms such as nitrate (NO_3^-), ammonia (NH_3), and nitrogen oxides (NO_x and N_2O) (summarized here as Nr). Since the 1980s, Denmark has attempted to reduce the release of nitrogen (N) into the environment by implementing regulations that limit manure application per hectare of crops based on the number of animals per farm (the Harmony Rule) and promote the use of catch crops to meet target goals (Sommer and Knudsen, 2021). However, significant amounts of manure are still applied to Danish farmlands, primarily due to the substantial livestock sector. In 2020 alone, approximately 215,800 tons of nitrogen from manure were used (Sommer and Knudsen, 2021). Therefore, it is imperative to evaluate management strategies that optimize the use of livestock manure and catch crops while incorporating crop residues and above- and below-ground biomass of grass when grasslands are plowed, all while minimizing environmental impact.

The incorporation of crop residues, a carbon farming practice, tends to increase soil organic carbon (SOC) levels, although nitrous oxide (N_2O) emissions may also increase (Carvalho et al., 2017; Guenet et al., 2021). On the other hand, the incorporation of catch crops has the potential to reduce nitrogen leaching (Knudsen, 2012a, 2012b; Vogeler et al., 2023) by initiating nitrogen immobilization. Catch crops capture mineral N in the biomass, which after incorporation into the soil and mineralization may become available for subsequent main season crops, potentially reducing fertiliser applications (e.g., Vos and van der Putten, 2001; Thorup-Kristensen, 1994; Thorup-Kristensen and Nielsen, 1998).

In November 2024, the Danish Parliament passed the Agreement on a Green Denmark, which includes an investment of 5.8 billion €, plus an additional 1.34 billion € from the Novo Nordisk Foundation to convert 250,000 ha of agricultural land into forests and nature reserves. The goal is to fulfil the Water Framework Directive's objectives by 2027 and reduce greenhouse gas emissions (Regeringen, 2024). Higher regulatory pressure will be temporarily set in agriculture, related to the reduction requirement for nitrogen (N) loads to coastal water bodies, if the land conversion has not achieved the required reduction by 2027. To achieve sufficient reduction of the nitrogen load to coastal waters, a new emission-based regulation will be implemented for all farms. Each farm will receive a reduction target for nitrogen loads to specific coastal bodies of water to be met by 2027. Financial contributions will include reallocations and reserves from the EU Common Agricultural Policy.

Additionally, Denmark will re-wet 140,000 ha of carbon-rich, drained peatlands to reduce GHG emissions. As the first country to implement a climate tax on GHG emissions from livestock, Denmark will introduce a tax of 16 €/t CO_{2e} in 2030 and 40 €/t CO_{2e} in 2035. A base reduction of 60 % for emissions that currently cannot be mitigated through recognized technologies will lower the total tax burden on the agricultural sector. Starting in 2028, there will be a tax of 5 €/t CO2e on emissions from drained peatlands used for agriculture and a tax of 100 €/t CO2e on emissions from agricultural lime. These taxes have a calculated potential to reduce emissions by 1.8–2.6 million tons of CO_{2e} in 2030.

Currently, Danish farmers are required to grow catch crops on 10.7 % or 14.7 % of their total possible autumn cropping area, depending on whether they use less than or more than 80 kg N ha^{-1} of organic fertiliser. Additionally, there are requirements for targeted catch crops and extra catch crops related to application of manure and to specific areas of the country (Blicher-Mathiesen and Thorsen, 2025).

These new agricultural sector regulations require knowledge of how changes in cropping, fertilisation, and mitigation measures, such as catch crops, can contribute to meeting the nitrogen reduction target for coastal water bodies and lowering greenhouse gas emissions, which reduces farmers' tax costs.

The ongoing shift in the Danish livestock sector towards larger present farmers with the challenge of maintaining the right balance between arable land and manure supply. This challenge is even more pronounced in areas where there is a shortage of land available for livestock farming. The challenge arises due to the Danish "harmony rule," which imposes strict limits on the amount of manure that can be applied per hectare, effectively capping the number of livestock per unit of land. This regulation creates a need for more arable land to ensure compliance. For example, farmland near livestock operations is predominantly fertilized with manure, while farmland away from livestock operations may be fertilized with synthetic fertilisers or a mix of synthetic and organic fertilisers. Studies show that keeping manure on the farm is the most cost-effective option. Though the total manure use quota must be followed, spreading livestock manure on neighbouring farmland can lead to overfertilization of nearby fields. Farms farther away from livestock operations may face the opposite problem (Jacobsen, 2011; Asai et al., 2014). These correspond to three types of croplands based on the type of nitrogen supplied: organic manure dominated, synthetic fertiliser dominated, and mixed. The goal of this study is to assess the environmental performance of different fertiliser, residue (retention or removal), and catch crop management schemes with regard to its effectiveness in reducing environmental nitrogen losses and improving the soil net greenhouse gas (GHG) balance in Danish agricultural systems. To do this, we used detailed site information on farming activities of farmers participating in the Loop-program, and supplementary information on soil, climate and crops as summarized in Table 1. To finally run the assessment, we used the LandscapeDNDC (LDNDC) framework. LDNDC is well-suited for site-specific applications and facilitates the efficient calculation and aggregation of regional or national greenhouse gas (GHG) inventories. Moreover, it can be integrated with other regional models, such as hydrological models, to account for lateral water and nutrient transport, as well as interactions between various landscape components. The framework also ensures consistent simulation of soil and vegetation dynamics during land-use or land management changes (Haas et al., 2013). This study hypothesizes that optimized crop residue management (whether through retention or removal) and the incorporation of catch crops can significantly reduce the environmental impact of various fertilisation strategies.

2. Materials and methods

2.1. Study area

This study includes analyses of field-level data collected from six Danish catchments between 2013 and 2019, as part of the National Monitoring Program for Water Environment and Nature, NOVANA (LOOP-program; in Danish: Landovervågningsprogrammet). The catchments are distributed across Denmark and vary in climate, soil

Table 1
Day of planting and harvesting, total N input, and livestock density tabulated as means for 2013–2019 as well as, elevation, mean precipitation, temperature, soil type and organic C in topsoil for individual LOOP catchments (sourced from the LOOP data).

Catchment	Crops	Planting Day of Year	Harvest Day of Year	TotN Input (Mean ± SE)	Livestock Density (DE ha-1)(Mean ± SE)	Elevation (m)	Climate		Soil	
							Prec. (mm)	Temp (°C)	Type	Organic C (0-30 cm) g kg^{-1}
	RAPE	234	216	201.24 ± 5.68	0.23 ± 0.02					
LOOP1 Højvads	SBAR	95	219	130.10 ± 2.60					80 % Sandy loam	2.1
Rende	WIWH	262	218	182.27 ± 1.90		3.30	650.30	9.80	14 % Clay	(0–22.2)
	WIWH	257	228	150.86 ± 3.26	0.44 ± 0.03					
	SBAR	101	201	163.26 ± 8.88						
	RAPE	227	217	191.96 ± 8.00						
	WBAR	261	201	179.14 ± 23.94						
	PEAS	122	276	246.53 ± 8.75					72 % Coarse sand	
LOOP2	OATS	91	228	111.40 ± 20.40					17 % Fine	3.3
Odderbæk	POTA	107	253	84.50 ± 0.00		12.60	849.20	8.70	sand	(0–33.2)
	OATS	105	212	124.69 ± 17.35	0.74 ± 0.06					
	PEAS	124	276	83.39 ± 8.20						
	RAPE	226	223	182.03 ± 9.64						
	SBAR	106	227	87.54 ± 7.10						
LOOP3	WBAR	258	206	138.48 ± 4.63					70 % Sand-mixed clay	
Horndrup Bæk	WIWH	261	222	130.08 ± 5.29		39.80	806.10	9.00	24 % Clay-mixed sand	1.7 (0–22.6)
	WIWH	263	223	162.60 ± 3.94	1.06 ± 0.03					
	WBAR	262	205	144.00 ± 4.41						
	PEAS	119	272	73.60 ± 0.00						
	RAPE	231	218	170.27 ± 5.39					86 % Sand-mixed clay	
LOOP4 Lillebæk	SBAR	98	225	118.14 ± 6.60		7.40	804.90	9.70	4 % Clay-mixed sand	1.3 (0.8–10.1)
	OATS	122	238	137.80 ± 39.05	1.61 ± 0.05					
	PEAS	120	275	124.01 ± 8.46						
	POTA	105	277	209.63 ± 13.22						
	RAPE	209	214	145.68 ± 11.52						
	SBAR	98	211	147.93 ± 12.18					67 % Coarse sand	
	WBAR	267	202	164.61 ± 22.24					18 % Clay-mixed sand	
LOOP6 Bolbro Bæk	WIWH	263	221	144.75 ± 7.34		23.40	1003.50	9.20	14 % Humus	4.0 (1–20.6)
	WBAR	261	205	149.65 ± 4.41	1.51 ± 0.03					
	OATS	106	224	93.14 ± 9.03						
	RAPE	231	210	184.04 ± 4.77						
	SBAR	99	225	115.66 ± 2.11					76 % Sandy clay	
LOOP7 Hulebæk	WIWH	261	224	159.34 ± 2.47		38.5	682.90	9.30	20 % Clay	1.8 (0–28.4)

DE (gennemsnitlig husdyrtæthed) stands for “Average Livestock Density” in Denmark, which corresponds to 100 kg of total nitrogen in the manure after manure storage and correspond approximately to manure produced by one cow per hectare.
The harvest day for winter crops typically occurs in the year following their planting. For example, winter wheat (WIWH) is sown on day 261 of the current year and harvested on day 221 of the following year.

types and agricultural utilization. Specifically, LOOP 1 encompasses 980 ha, with 73 % dedicated to agriculture; LOOP 2 spans 1140 ha, with 98 % utilized for agricultural purposes; LOOP 3 covers 550 ha, with 82 % allocated to agriculture; LOOP 4 includes 470 ha, with 89 % used for agricultural activities; LOOP 6 consists of 820 ha, with 99 % devoted to agriculture; and LOOP 7 comprises 1520 ha, with 78 % employed in agricultural use. These catchments cover to a large extend the range of soil types, climatic conditions, and agricultural practices found in Denmark. The monitoring program provides comprehensive insights into catchment-specific agricultural practices, including crop types, the presence or absence of catch crops, cropping calendars, and details on the timing, type, and amount of synthetic and organic fertiliser applications (Grant et al., 2011; Blicher-Mathiesen et al., 2014). Table 1 presents information about the activities in catchment areas.

2.2. Study design

We categorized fields based on their management during 2013–19, distinguishing between those dominated by organic fertiliser, synthetic fertiliser, or a blend of the two. We categorized fields with varying characteristics into distinct groups according to their fertilisation schemes to facilitate comparative analysis. We then assessed their functionality by simulating their actual crop rotation cycles over the study period. Domination by either organic or synthetic fertiliser was determined if it accounted for more than 80 % of the total amount, while a blend was considered if each contributed 48–52 %. Other ratios that were not counted as the previous ones were counted as others. According to the analysis, of the total area of the separated fields, 22.3 % (19.2–26.6) were labeled as organic fertiliser dominated (OFD), 31.2 % (29.3–34.8) as synthetic fertiliser dominated (SFD), 3.9 % (3.4–4.9) as blending (BLN), and the remaining percentage as other. Field characteristics in different cropping practices for comparative analysis is shown in Table 2.

Table 2
Field characteristics in different cropping practices for comparative analysis (Sourced from the LOOP Program).

Cropping Practice	SOIL		Management	
	Fractional cover of different soil textures [%]	SOC [%]	ORG. [kg N ha^{-1} yr^{-1}]	SYN. [kg N ha^{-1} yr^{-1}]
OFD	Sand: 89.67, Sandy Loam: 10.15, Sandy Clay: 0.18	3.34 (3.23–3.54)	165 (157–175)	14 (11–17)
SFD	Sandy Loam: 26.91, Sandy Clay: 73.9	2.23 (1.90–2.69)	0 (0–1)	130 (122–140)
BLN	Sand: 8.75, Sandy Loam: 77.59, Sandy Clay: 13.46, Clay Loam: 0.20	2.38 (1.96–2.81)	103 (86–127)	104 (86–126)

Note: Soil characteristics, including soil texture (Adhikari et al., 2013), soil organic carbon (SOC) (Adhikari et al., 2014).

2.3. Modelling cropping practices

The modelled cropping practices assessed the impact of crop residue management, focusing on retention versus removal, as well as the incorporation of catch crops, on crop yield and environmental outcomes. Presently, there is limited evidence suggesting that some farmers employ catch crops, as adoption rates vary significantly between regions due to differences in soil type, climate, and financial incentives. While some studies highlight the benefits of catch crops for soil health and nutrient retention (Doltra and Olesen, 2013; Eriksen and Thorup-Kristensen, 2002; Munkholm and Hansen, 2012; Vogeler et al., 2022), others point to challenges such as species selection, labour demands, and additional costs, which may hinder widespread adoption (Aare and Hauggaard-Nielsen, 2019; Knudsen, 2012a, 2012b). These contrasting perspectives make it a compelling reason to test the cropping practices further, as understanding both the potential advantages and challenges will help in determining the conditions under which catch crops can be most effectively utilized in Danish agricultural systems.

In this study we defined that the management of crop residues exhibited variability for the same field over the period from 2013 to 2019. Keeping crop residues on the field is recognized as an effective strategy for enhancing soil organic matter (SOM) levels and promoting carbon sequestration (Minasny et al., 2017). However, this practice also leads to a notable increase in nitrous oxide (N_2O) emissions compared to the removal of residues, potentially diminishing the benefits of carbon sequestration (Abalos et al., 2022). This effect is particularly pronounced for aboveground residues, which tend to release more N_2O than root residues, as they often contain higher amounts of readily degradable organic matter (Rummel et al., 2020). Given the trade-offs between carbon sequestration and N_2O emissions, testing the effects of residue retention versus removal becomes a crucial practice to explore. This will provide valuable insights into optimizing residue management practices to maximize carbon storage while minimizing greenhouse gas emissions, thus improving the sustainability of Danish agricultural systems. For this reason, in this study, for each category of fields labeled as organic fertiliser dominated (OFD), synthetic fertiliser dominated (SFD), and blending (BLN), we modelled practices with or without catch crops, and with either complete retention or complete removal of crop residues. As a result, the study included twelve different cropping practices that examined the production and environmental impacts per unit of output (crop yield) for the major crops within the LOOPs. These practices, identified by specific codes, were designed to explore the impact of different agricultural practices on crop outcomes. The cropping practices included:

- **OFD-CR-CC:** Fields dominated by organic fertiliser, with complete removal of crop residue and no catch crop.
- **SFD-CR-CC:** Fields dominated by synthetic fertiliser, with complete removal of crop residue and no catch crop.
- **BLN-CR-CC:** Fields with blending fertiliser, with complete removal of crop residue and no catch crop.
- **OFD + CR + CC:** Fields dominated by organic fertiliser, with complete retention of crop residue and a catch crop.
- **SFD + CR + CC:** Fields dominated by synthetic fertiliser, with complete retention of crop residue and a catch crop.
- **BLN + CR + CC:** Fields with blending fertiliser, with complete retention of crop residue and a catch crop.
- **OFD-CR + CC:** Fields dominated by organic fertiliser, with complete removal of crop residue but with a catch crop.
- **SFD-CR + CC:** Fields dominated by synthetic fertiliser, with complete removal of crop residue but with a catch crop.
- **BLN-CR + CC:** - Fields with blending fertiliser, with complete removal of crop residue but with a catch crop.
- **OFD + CR-CC:** Fields dominated by organic fertiliser, with complete retention of crop residue but without a catch crop.
- **SFD + CR-CC:** Fields dominated by synthetic fertiliser, with complete retention of crop residue but without a catch crop.
- **BLN + CR-CC:** Fields with blending fertiliser, with complete retention of crop residue but without a catch crop.

In this study, we employed the actual crop rotations observed in the LOOPs and as reported by farmers. Crops were categorized based on the type of field they were associated with, i.e., organic fertiliser dominated fields, synthetic fertiliser dominated fields or Mixed (using a mix of synthetic and organic fertiliser). Therefore, the crop rotations were not predefined but used in our simulations to reflect the real-world practices observed in the LOOPs. Furthermore, the complete retention of crop residues meant that all residues were left on the field (except for silage maize), while the presence or absence of a catch crop was a determining factor in certain practices. For this study, rapeseed is used as the catch crop. These delineated typologies provided a comprehensive overview for assessing the influence of field management on crop performance and environmental impact.

2.4. Model description

LandscapeDNDC (LDNDC) (https://ldndc.imk-ifu.kit.edu/) is a process-based modelling framework capable of simulating carbon (C), nitrogen (N), and water processes in cropland, grassland, and forest ecosystems (Haas et al., 2013). This framework uses a number of different modules to simulate plant growth and other processes, including plant physiology (PlaMox) (Kraus et al., 2016; Liebermann et al., 2019), micro-climate (CanopyECM) (Grote et al., 2009), water balance (WatercycleDNDC) (Li et al., 1992; Kiese et al., 2011), air chemistry (airchemistryDNDC), and soil biogeochemistry (MeTrx) (Kraus et al., 2015). The model has been widely applied in diverse studies, showcasing its versatility and reliability. Takeda et al. (2024) used it to improve nitrogen budget simulations in tropical sugarcane systems, demonstrating enhanced accuracy in predicting N_2O and N_2 emissions. Fuchs et al. (2024) applied the model in Sub-Saharan Africa, showing that intercropping legumes improved long-term soil carbon and nitrogen stocks while sustaining productivity. Haas et al. (2022) applied the model to assess the long-term impact of residue management on soil organic carbon stocks and nitrous oxide emissions across European croplands. Kraus et al. (2022) validated the model's utility at a national scale in the Philippines by evaluating alternate wetting and drying practices for rice, which significantly reduced greenhouse gas emissions. Smerald et al. (2023) demonstrated how redistributing nitrogen fertilisers globally could close yield gaps while minimizing environmental harm, further cementing the model's role in guiding sustainable agricultural practices. These studies underline the model's credibility and broad applicability in advancing environmental and agricultural research.

With respect to Denmark, our study area, the model has been validated for Denmark using experimental data encompassing soil organic carbon (SOC) stocks, crop productivity, and soil greenhouse gas (GHG) emissions. Kollmer (2023) optimized the model's plant physiological and soil biogeochemical parameters using data from a long-term experiment conducted in Askov, Denmark. This optimization successfully simulated a continuous increase in SOC stocks over time, reflecting stable conditions in long-term dynamics of crop biomass and soil organic carbon. Similarly, Grados et al. (2024) validated the model's ability to simulate N_2O emissions, using data from a diversified long-term experiment initiated in 1997 in Foulum, Denmark. Their findings indicated that the model's simulation of N_2O emissions fell within the unsystematic error region, with a standardized RMSE of 2.03 g N_2O-N ha^{-1} d^{-1}, highlighting its robustness in representing greenhouse gas emissions under local conditions.

Further validation was conducted by Rahimi et al. (2024) using data from the six LOOP catchments in Denmark. This study demonstrated the model's capability to accurately simulate the nitrogen surplus and crop yields for nine major crops (winter wheat, spring barley, rapeseed, winter barley, silage corn, peas, sugar beet, potato, and oats.). The overall R^2 for crop yield simulations was 0.77, with the highest accuracy observed for winter barley ($R^2 = 0.78$) and the lowest for potato yields ($R^2 = 0.41$).

The parameter ranges and inputs utilized in the current study align with those established by Rahimi et al. (2024).

2.5. Evaluation criteria

In this study, we compared different cropping practices using two indicators to make them comparable, regardless of their input levels. The first indicator is Nitrogen Use Efficiency (NUE), defined as follows:

$$NUE = \frac{Y}{FN} * 100$$

where Y is the crop yield (kg N ha^{-1}), and FN is the amount of fertiliser nitrogen applied (kg N ha^{-1}).

The second indicator is the soil net GHG balance (GHG_{bal}), calculated using the following equations:

$$GHG_{bal} = \mathrm{GHGN2O} - \Delta SOC$$

Note that negative values denote a net flux of GHGs from the atmosphere to the soil.

The contribution of N_2O emissions associated with fertiliser application of fertilisers to fields is calculated as follows:

$$\mathrm{GHGN2O} = (\Sigma N2Odir + \Sigma N2Oindir) \times CF$$

Here, $\Sigma N2O$dir is the sum of direct field-scale soil N_2O emissions as simulated by the LandscapeDNDC model. $\Sigma N2O$indir, i.e. N_2O emissions due to NO_3^- leaching and NH_3 volatilisation, to N loss pathways simulated by the model, were calculated using the approach reported in the 2019 refinement of the 2006 IPCC guidelines (IPCC, 2019). I.e., it is assumed that 1.1 % of leached NO_3^- and 1 % of volatilized NH_3 are lost to the environment as N_2O. CF is the conversion factor used to convert total N_2O emissions to their CO_2 equivalent.

The contribution of the annual change in soil organic carbon (ΔSOCS) (down to 1 m) to the field scale soil net GHG balance is calculated as follows:

$$\Delta SOC = \frac{Cn - C1}{n} \times CF$$

Where, Cn is the total soil organic carbon stock down to a soil depth of 1 m of year n, $C1$ is the SOC of the first year of the simulation period (n), and CF is the conversion factor used to convert SOC from carbon to CO_2 equivalents (=3.67).

2.6. Statistical analysis

In this study, the Analysis of Variance (ANOVA) test was employed to analyze the statistical differences between the different states concerning their yield and environmental impacts. Following the ANOVA analysis, we conducted a Tukey's Honestly Significant Difference (HSD) (Tukey, 1949) test as a post-hoc measure. The Tukey HSD test provided an understanding of the significance and magnitude of differences between pairs of cropping practices, allowing us to analyze the relative impacts of each field management.

3. Results

3.1. Yield performance of different cropping practices

Fig. 1 shows the average yield for different fertilisation and residue management practices. For all three fertilisation strategies (BLN, OFD and SFD) the highest average yield is obtained with crop residue incorporation but without a catch crop (+CR-CC). For the fertilisation strategies that include organic fertiliser (BLN and OFD), the removal of crop residues (-CR-CC) makes very little difference to yields (−1 %). The addition of catch crops (+CR + CC and -CR + CC) reduces yields by 2–11 % compared to +CR-CC. With synthetic fertilisation (SFD) the addition of a catch crop (+CR + CC) makes very little difference in yield (−1 %), while the removal of crop residues (-CR + CC and -CR-CC) results in a small yield reduction (2–4 %).

Yield differences between different fertilisation strategies (BLN, OFD and SFD) depend strongly on fertiliser application rates. As shown in Fig. 1, for winter wheat similar application rates (BLN 284 kg N ha^{-1} yr^{-1}, OFD 204 kg N ha^{-1} yr^{-1} and SFD 307 kg N ha^{-1} yr^{-1}) result in little difference in yield (ranging from 3.76 % - 4.22 %). However, for

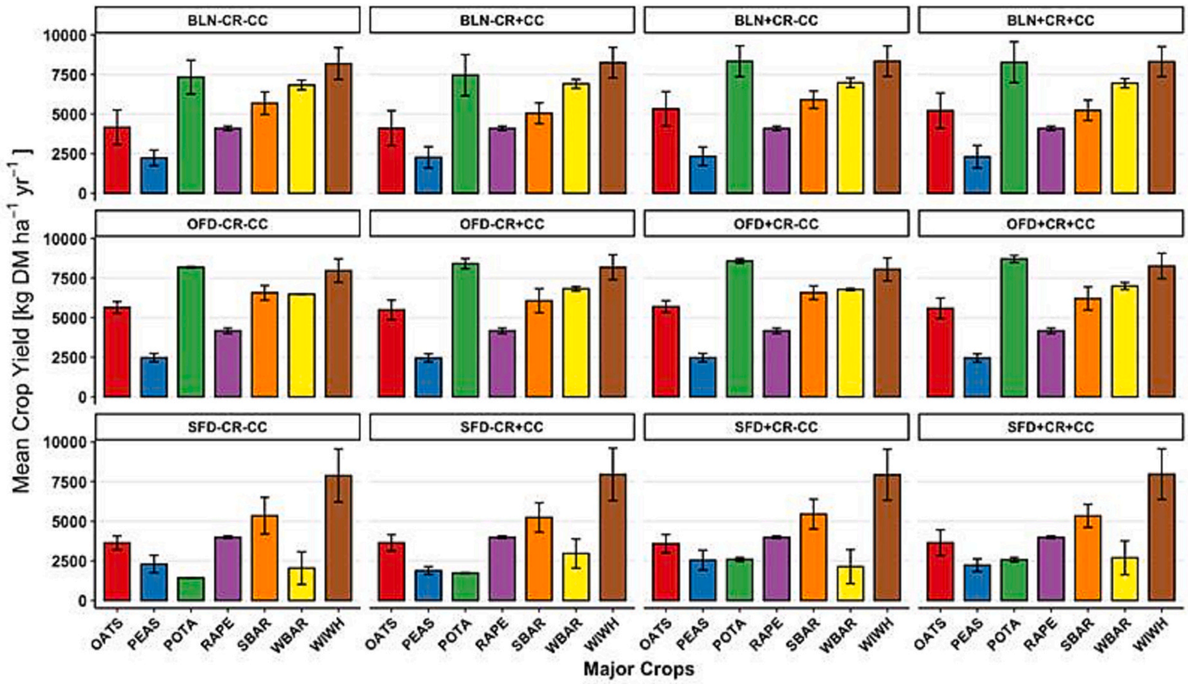

Fig. 1. Mean Crop Yield [kg DM ha^{-1} yr^{-1}] ± SE of the different field with fertilisation practices studied for major crops across all catchments between 2013 and 2019. OATS: oats; PEAS: peas; POTA: potato; RAPE: rapeseed; SBAR: spring barley; WBAR: winter barley; and WIWH: winter wheat. BLN: Blended; OFD: Organic Fertiliser Dominated fields; and SFD: Synthetic Fertiliser Dominated fields. -CR-CC: Crop Residue Removed and No Catch Crop; -CR + CC: Crop Residue Removed plus Catch Crop; +CR-CC: Crop Residue incorporated and NO Catch Crop; +CR + CC: Crop Residue Incorporated plus Catch Crop.

potatoes (BLN 260 kg N ha^{-1} yr^{-1}, OFD 236 kg N ha^{-1} yr^{-1} a and SFD has low fertiliser N input) and winter barley (BLN 264 kg N ha^{-1} yr^{-1}, OFD 247 kg N ha^{-1} yr^{-1} and SFD 73 kg N ha^{-1} yr^{-1}), differences in the fertiliser application rate result in large differences in yield (ranging from 8.7 % - 318.7 % for potatoes and 1.89 % - 159.7 % for winter barley).

3.2. Nitrate leaching losses

Fig. 2 shows the modelled average nitrate ($NO_3^{-}$$^{-}$) leaching rates for the different management practices. All three fertilisation treatments show much lower NO_3^{-}- leaching when catch crops are grown. For example, comparing -CR-CC to -CR + CC results in a difference in NO_3^{-}-leaching of BLN: 16.7 kg N ha^{-1} yr^{-1} (a decrease of 65.1 %), OFD: 46.0 kg N ha^{-1} yr^{-1} (a decrease of 71.4 %) and SFD: 17.1 kg N ha^{-1} yr^{-1} (a decrease of 53.9 %). The incorporation of crop residues results in a much smaller reduction in NO_3^{-}- leaching. For example, comparing -CR-CC to +CR-CC results in BLN: 9.1 kg N ha^{-1} yr^{-1} (a decrease of 35 %), OFD: 2.0 kg N ha^{-1} yr^{-1} (a decrease of 3.1 %) and SFD: 7.0 kg N ha^{-1} yr^{-1} (a decrease of 22.0 %) difference in $NO_3^{-}$$^{-}$ leaching.

3.3. Gaseous N losses (NH_3, NO, N_2O + N_2)

Fig. 3 shows the average gaseous N loss for different cropping

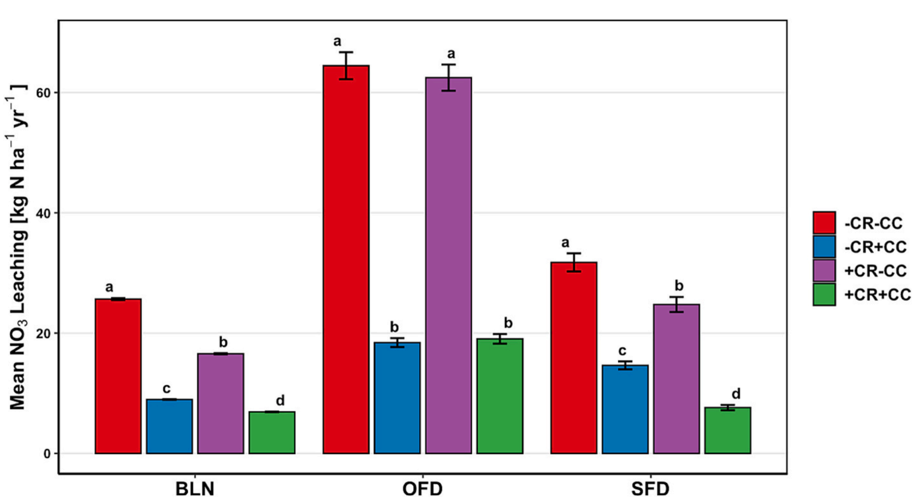

Fig. 2. Mean modelled annual nitrate ($NO_3^{-}$$^{-}$) leaching ± SE across all catchments, major crops, and all study years (2013–2019) for the different cropping practices studied. BLN: Blended; OFD: Organic Fertiliser Dominated fields; and SFD: Synthetic Fertiliser Dominated fields. -CR-CC: Crop Residue Removed and No Catch Crop; -CR + CC: Crop Residue Removed plus Catch Crop; +CR-CC: Crop Residue incorporated and NO Catch Crop; +CR + CC: Crop Residue Incorporated plus Catch Crop. Different letters indicate statistically significant differences between the cropping practices in each field.

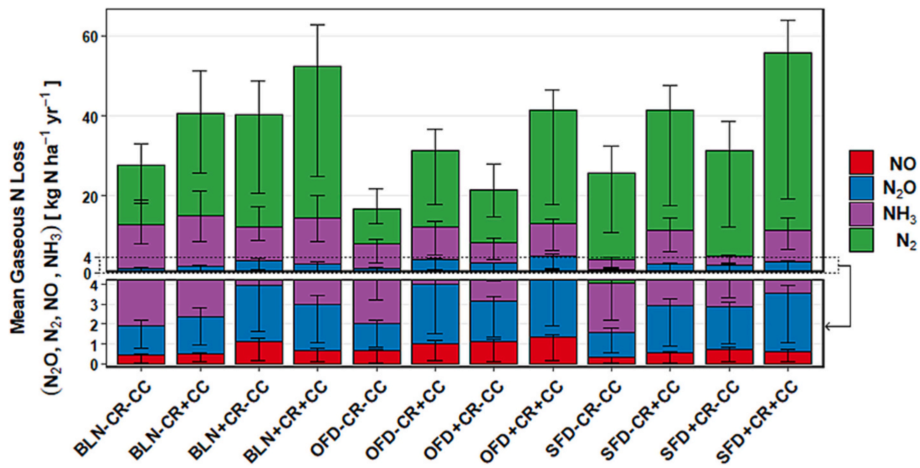

Fig. 3. Mean annual gaseous N losses ± SE in form of N_2, N_2O, NO and NH_3 across all catchments and all study years (2013–2019) for the different cropping practices studied. The upper panel shows total N losses, while the lower panel zooms in on the 0–4 kg N ha^{-1} yr^{-1} range to highlight small NO emissions that are otherwise hard to see in the upper panel. BLN: Blended; OFD: Organic Fertiliser Dominated fields; and SFD: Synthetic Fertiliser Dominated fields. -CR-CC: No Crop Residue and No Catch Crop; -CR + CC: No Crop Residue but have Catch Crop; +CR-CC: Crop Residue present without Catch Crop; +CR + CC: Contains both Crop Residue and Catch Crop.

practices are shown. Across all fertilisation treatments gaseous N losses are lowest in the absence of crop residue incorporation and a catch crop (-CR-CC) and highest when both these management options are implemented (+CR + CC). The differences are similar for the three fertilisation strategies and comparing +CR + CC with -CR-CC results BLN: 24.3 kg N ha^{-1} yr^{-1} (an increase of 94.4 %), OFD: 22.8 kg N ha^{-1} yr^{-1} (an increase of 98.7 %), SFD: 24.8 kg N ha^{-1} yr^{-1} (an increase of 79.2 %).

The trend for ammonia emissions as shown in Fig. 3 is much less pronounced than for total gaseous losses. The tendency is for catch crops to increase ammonia emissions and for crop residue incorporation to decrease emissions. For all fertiliser treatments -CR + CC shows the highest ammonia emissions and + CR-CC the lowest, with differences of 2.9 kg N ha^{-1} yr^{-1} (an increase of 45.7 %) for BLN, 3.6 kg N ha^{-1} yr^{-1} (an increase of 38.1 %) for OFD and 2.1 kg N ha^{-1} yr^{-1} (an increase of 34.2 %) for SFD.

Regarding gaseous nitrogen losses from different fertilisation strategies, the comparison should be made as a percentage of the total N input. In this context, when comparing N_2 + NH_3 and NO + NH_3 losses across different strategies, fields predominantly using synthetic fertilisers (SFD) exhibited the highest rates. These rates were 27.8 kg N ha^{-1} yr^{-1}, with a relative percentage of 16.9 % (11.3 % - 23.3 %), and 1.8 kg N ha^{-1} yr^{-1}, with a relative percentage of 1.8 % (1.4 % - 2.1 %), respectively.

3.4. *Comparative analysis of crop NUE across different cropping practices*

Fig. 4 shows the average crop NUE for different cropping practices. Within each fertiliser treatment, the differences in NUE between different management options (+-CR + -CC) are small compared to the standard error, which was derived on basis of the annual yields for the period 2013–2019. When comparing the different fertiliser treatments, there is a trend towards higher NUE with higher organic fraction of the fertiliser. For example, for -CR-CC the NUE for BLN is 11.5 % higher than SFD and OFD is 45.5 % higher than SFD.

3.5. *Comparative analysis of soil net GHG balance across different cropping practices*

The soil net GHG balance in various cropping practices, as depicted in Fig. 5, exhibits significant dependence on management practices.

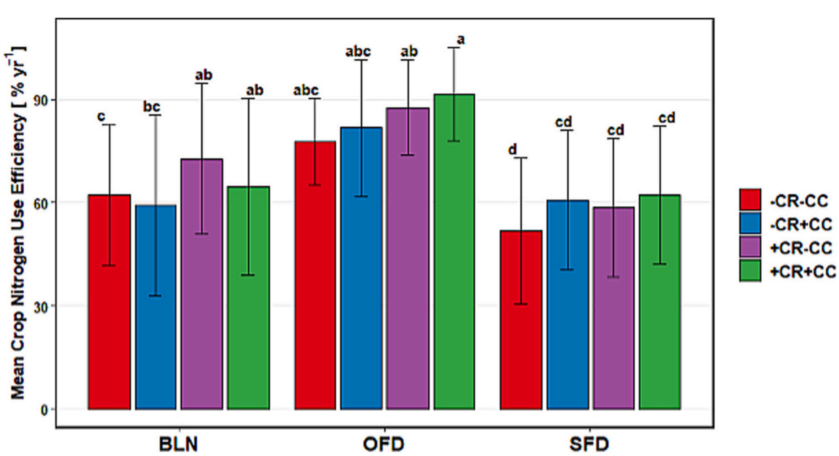

Fig. 4. Mean annual crop NUE of the different field and fertilisation practices studied. Given are mean values ± SE across all catchments and study years (2013–2019) for the three main fertilisation practices studied. BLN: Blended; OFD: Organic Fertiliser Dominated fields; and SFD: Synthetic Fertiliser Dominated fields. -CR-CC: Crop Residue Removed and No Catch Crop; -CR + CC: Crop Residue Removed plus Catch Crop; +CR-CC: Crop Residue incorporated and NO Catch Crop; +CR + CC: Crop Residue Incorporated plus Catch Crop. An Analysis of Variance (ANOVA) performed on the 12 cropping practices revealed a statistically significant difference with respect to NUE.

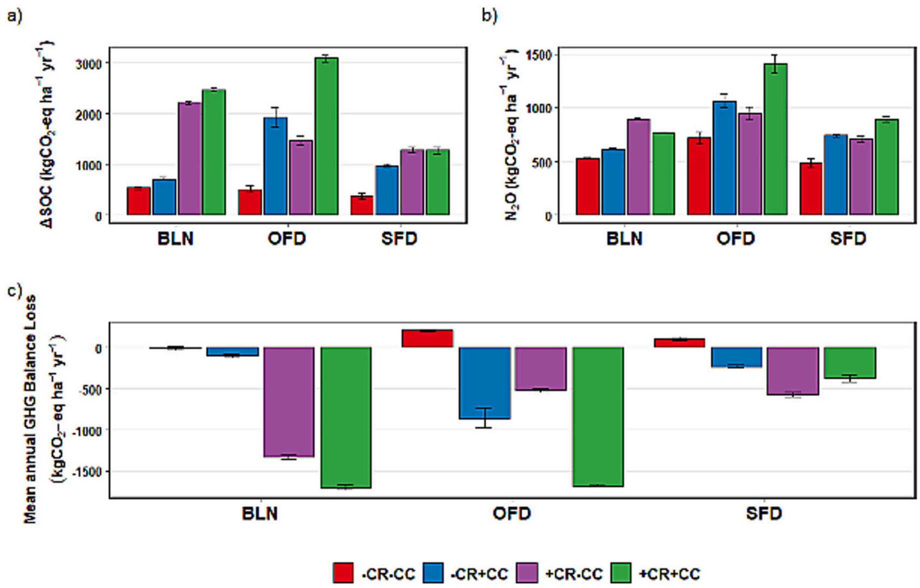

Fig. 5. Mean annual soil net GHG balance of the different cropping practices for the years 2013 to 2019 and across all studied catchments. (a) Changes in soil organic carbon stocks. (b) Soil N_2O emissions. (c.) Total mean annual soil GHG balance. The soil net GHG balance is calculated as the sum of SOC-sequestered CO_2 and direct and indirect N_2O emissions, converted to CO_2 equivalents. Negative values imply that cropping practices function as a net sink of GHGs. BLN: Blended; OFD: Organic Fertiliser Dominated fields; and SFD: Synthetic Fertiliser Dominated fields. -CR-CC: No Crop Residue and No Catch Crop; -CR + CC: No Crop Residue but have Catch Crop; +CR-CC: Crop Residue present without Catch Crop; +CR + CC: Contains both Crop Residue and Catch Crop.

Under the -CR-CC management strategy, there is a decline in soil carbon stocks. However, through practices such as crop residue incorporation and catch crops, the system can transition into a net greenhouse gas absorber.

With regard to direct and indirect emissions of N_2O, it's evident that they play a crucial role in overall greenhouse gas dynamics. Notably, as shown in Fig. 5(c), the BLN and OFD strategies show promising results, with potential net greenhouse gas absorption rates of 1703.6 $kgCO_2$_eq ha^{-1} yr^{-1}) and 1678.3 $kgCO_2$_eq ha^{-1} yr^{-1}) respectively, under the +CR + CC management approach. Conversely, the SFD strategy achieves the highest net greenhouse gas absorption rate of 573.9 ($kgCO_2$-_eq ha^{-1} yr^{-1}) under a + CR-CC management regime.

4. Discussion

This study used a process-based modelling framework called LandscapeDNDC to assess the environmental performance of twelve different cropping practices, using data on land use and management from six catchments in Denmark. The result of the model simulations shows a good agreement with field measurements in Denmark and nearby countries. For example, Askegaard et al. (2011) found that in Danish conditions, the use of catch crops resulted in an average reduction in nitrate leaching of approximately 20 kg N ha^{-1}. This compares well to our results in Fig. 2, which show a reduction of 16.7 kg N ha^{-1}. Li et al. (2021) found that in soils with sandy loam, silty clay loam, and silt loam textures, crop residue incorporation resulted in a 14.4 % reduction in nitrate leaching, as compared to 35.4 % in our results. However, the major soil condition of Denmark has been observed to be coarse sand (Adhikari, 2013). Therefore, the notable difference in reduction percentages could be attributed to variations in local climate, soil composition, and specific agricultural practices between the study regions. However, unlike other studies (Haas et al., 2002; Knudsen et al., 2006; Korsaeth, 2008) we found that organic fertilisation (OFD -CR-CC 52.8 %) resulted in a higher fraction of fertiliser nitrogen leaching as compared to synthetic fertilisation (SFD -CR-CC 26.1 %). This is likely due to the considerably higher fertilisation rates applied to organically fertilized fields (179 kg N ha^{-1} for OFD vs 130 kg N ha^{-1} for SFD).

With respect to yield, our findings as shown in Fig. 1 depict that the addition of catch crops reduces yield, which agrees with the findings of Deines et al. (2023). Our results show that there is no single management option that is always superior to all other options. Instead, field management involves trade-offs between yield and different forms of environmental pollution. This is clearly the case for fertiliser strategies, where our results show no significant difference between yields (modelled differences are primarily due to fertiliser application rates) but large differences between environmental impacts. Looking only at NUE in Fig. 4 would suggest that the OFD strategy has the lowest environmental impact, with up to 90 % of the applied fertiliser exported in the harvest. However, significant mining of soil organic nitrogen means that the environmental impact can still be high. For example, nitrate leaching as shown in Fig. 2 is highest in the OFD strategy, even when normalising with respect to fertiliser input rates. The SFD strategy has the lowest ammonia volatilisation (Fig. 3) but shows limited potential to accumulate carbon and therefore absorb CO_2 from the atmosphere as shown in Fig. 5(c). It also has a low NUE. The BLN strategy shows very low nitrate leaching, but this is partly offset by having the highest ammonia volatilisation rate. In terms of greenhouse absorption potential, it is similar to the OFD strategy and considerably better than the SFD strategy.

Taking into account all these trade-offs, our results point towards BLN being the best strategy in a Danish context. The very low nitrate leaching rates are an important consideration in Danish agriculture, where high precipitation rates, sandy soils and high fertilisation rates have resulted in a significant problem with nitrate pollution (Kyllingsbæk and Hansen, 2007; Adhikari, 2013; Jabloun et al., 2015). Furthermore, the BLN strategy should not be compared to the OFD or SFD strategies in isolation, but to a combination of the two. Unless there are substantial changes in livestock numbers in Denmark, the current manure production is insufficient for most Danish arable fields to implement an Organic Farming Directive (OFD) strategy. Oelofse et al. (2013) highlight the necessity for alternative strategies to ensure an adequate organic nutrient supply if conventional fertilisers are phased out in Denmark. Similarly, a widespread SFD strategy would result in the problem of how to dispose of unwanted manure. Comparing BLN to OFD and SFD results in BLN having a higher greenhouse gas absorption potential in addition to lower nitrate leaching losses. However, the cost is higher than the amount of ammonia volatilisation.

The question of whether or not to incorporate crop residues is also dependent on what trade-offs are most desirable in the context of Danish agriculture. Our results show that crop residue incorporation makes little difference to yields or NUE and only results in a small decrease in nitrate leaching. However, it significantly increases gaseous losses of NO, N_2O and NH_3, and at the same time leads to a large increase in carbon sequestration in the soil. In terms of the greenhouse gas balance, the increased carbon sequestration considerably outweighs the increased N_2O emissions, resulting in high net absorption of greenhouse gases. Thus, it is necessary to weigh the importance of greenhouse gas absorption against that of atmospheric pollutants such as NO and NH_3 when deciding on crop residue management strategies. Furthermore, it is important to note that not all crop residues are necessarily available for incorporation. Denmark uses approximately 23 % of crop residues for biogas production and uses a significant fraction for animal bedding (Scarlat et al., 2010). In both these cases the residues are partly returned to the soil via the spreading of digestate and the incorporation of animal bedding in manure.

Catch crop cultivation also results in trade-offs. The model predicts that the main crop experiences a small yield penalty due to catch crop cultivation, which aligns with the findings of Deines et al. (2023) and suggests the need to improve catch crop management to mitigate yield penalties. However, some other studies (Hansen and Djurhuus, 1997; Hansen et al., 2000) do not support our findings. Catch crop cultivation also leads to a large reduction in nitrate leaching and a modest increase in greenhouse gas absorption, but this must be set against an increase in gaseous emissions of NO, N_2O and NH_3. Given the acuteness of the nitrate leaching problem in Denmark, widespread adoption of catch crops is likely to be beneficial, despite the increased gaseous losses.

To mitigate the increased gaseous losses due to the adoption of catch crops and crop residue management, several fertiliser application techniques can be employed. One effective strategy is the use of slow-release fertilisers, which provide a steady supply of nitrogen, thereby reducing the peak periods of nitrogen availability that lead to gaseous losses. Additionally, the application of nitrification inhibitors can slow down the conversion of ammonium to nitrate, reducing nitrous oxide emissions. Placement of nitrogen fertilisers at greater depths (>5 cm) in the soil has also been found to be an effective method for minimizing gaseous losses (Van Kessel et al., 2013).

Another widely accepted strategy is to reduce the overall nitrogen application rate. This approach has been consistently shown to be effective in lowering gaseous emissions from agricultural fields (Venterea et al., 2012). By optimizing the amount of nitrogen applied to match crop needs more closely, farmers can reduce the risk of losses of nitrogen to the atmosphere. However, since agriculture is a significant source of greenhouse gas emissions in Denmark, the predicted increases in emissions of nitric oxide (NO) and ammonia (NH_3) due to the adoption of catch crops and crop residues could indeed exacerbate existing environmental problems.

The foreseeable challenge for large-scale adoption of blending organic and synthetic fertilisers (BLN) in Denmark could indeed be related to the efficient transport and management of manure. Denmark's agricultural landscape, characterized by intensive livestock production concentrated in certain regions and diverse crop cultivation in others, presents logistical hurdles for transporting manure to where it is needed most. But Incorporating livestock into the agricultural landscape offers a viable pathway to address the challenges associated with manure transport and support the widespread adoption of blending organic and synthetic fertilisers (BLN) in Denmark.

5. Study limitations and uncertainties

While this study provides valuable insights into the environmental and production impacts of various cropping practices, several limitations should be acknowledged. A major source of uncertainty in our study arises from concentrating on a single catch crop, specifically rape. In reality, farmers employ a variety of catch crops, each with distinct growth characteristics and nitrogen uptake efficiencies. The use of only one type of catch crop may not fully capture the variability in nitrogen leaching or its impact on soil nitrogen dynamics across different cropping systems.

Another limitation arises from the simplification of crop residue incorporation. In this study, we modelled two extremes i.e., complete crop residue retention (100 %) and complete removal (0 %). However, in practice, the percentage of residue incorporated can vary widely depending on factors such as field conditions, machinery capabilities, and management practices. Intermediate residue retention levels may yield different environmental outcomes, which could not be explored in this study due to the constraints of our model.

Additionally, uncertainties in crop parameterization and the use of generalized cultivars add to the complexity. For instance, while we have grouped wheat into a single category (e.g., Winter Wheat), farmers may use different cultivars with distinct growth patterns, yields, and nitrogen uptake rates, potentially leading to different environmental outcomes. In real-world farming, these variations could significantly influence the results but were not accounted for in our analysis.

Lastly, another key uncertainty is the variability in manure quality. The data used in this study does not explicitly account for differences in the nitrogen content, organic matter, and mineral composition of manure, which can vary significantly between farms, seasons, and livestock types. As a result, the environmental impacts associated with manure management may be oversimplified, and the model's ability to accurately represent the effects of manure on nitrogen cycling and greenhouse gas emissions are limited.

6. Conclusions

This study utilizes a process-based modelling framework called LandscapeDNDC to assess the environmental performance of different fertiliser, residue and catch crop management schemes regarding its effectiveness to reduce environmental nitrogen losses and improving the soil net GHG balance of Danish agricultural systems. According to the results presented in this study, it can be concluded that solely relying on either organic or synthetic nitrogen (N) is generally not beneficial for reducing excess nitrogen. This finding underscores the importance of mixing organic and synthetic N fertiliser applications, emphasizing the significance of manure transport and strategic distribution. This study focuses on comparing BLN with OFD and SFD, rather than directly comparing all the cropping practices against each other. The findings demonstrate the potential benefits of integrating both organic and synthetic fertilisers compared to relying solely on OFD or SFD practices individually. This study also established that Nitrogen Use Efficiency alone is insufficient for assessing the environmental impact of cropping systems. A comprehensive evaluation must also incorporate variables such as Nitrate leaching, Greenhouse gas balance and others to provide a more accurate assessment. Increasing the use of organic fertilisers and catch crops can transform soils into net sinks of greenhouse gases (GHGs) due to their potent carbon sequestration capacity, which overpowers the stimulatory effect on nitrous oxide (N_2O) emissions. Another notable finding is also that the incorporation of crop residues and catch crops leads to higher gaseous emissions (NO and NH_3), even though they help reduce nitrate leaching. This underscores the necessity of mitigating these impacts with improved fertilisation techniques, which may entail higher costs.

Moving forward, further research endeavours could explore the potential benefits and socio-economic implications of manure redistribution at a national scale to understand its scalability and feasibility when broadly applied. Moreover, examining the socio-economic implications and policy frameworks necessary to support widespread will be a direction to explore.

CRediT authorship contribution statement

Meshach Ojo Aderele: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Edwin Haas:** Writing – review & editing, Methodology, Conceptualization. **Andrew Smerald:** Writing – review & editing, Conceptualization. **Gitte Blicher-Mathiesen:** Data curation, Writing – review & editing. **Klaus Butterbach-Bahl:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jaber Rahimi:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, 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.

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Data availability

The authors do not have permission to share data.

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