



Climate efficiency of long-term nutrient management: Cross-site greenhouse gas responses in temperate cropping systems

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ABSTRACT

Long-term nutrient management is central to climate-smart agriculture, yet comparative evidence across crop rotations, soils, and fertilisation strategies remains limited. Fluxes of nitrous oxide, carbon dioxide and methane were quantified, together with crop productivity, across three German long-term experiments encompassing four cropping systems: silage maize following cover crops, potatoes under organic rotations, and Persian clover and winter rye under contrasting nutrient management strategies. Gas fluxes were measured using dynamic chamber systems, with intensified sampling after fertilisation, tillage, cutting, and freeze–thaw cycles. Across sites, greenhouse gas fluxes were largely driven by short-term responses to weather and management events. Depending on the treatment, annual nitrous oxide emissions varied by more than two orders of magnitude, ranging from 10.8 to 26.8 in maize, 2.22–2.54 in potatoes, 0.67–4.71 during the clover phase and 0.86–9.24 kg N ha⁻¹ yr⁻¹ during the winter rye phase. Cover-crop treatments significantly affected nitrous oxide emissions in maize, with lower emissions following Phacelia and a four-mixed cover crop than after Oat or Fallow, whereas organic fertilisation strategies showed no significant effects. Nutrient replacement strategies significantly influenced emissions during the clover phase, with higher emissions under farmyard manure-only and combined mineral-organic fertilisation with liming than under complete mineral fertilisation or nitrogen-omission treatments. Carbon dioxide emissions, ranging from 8 to 24 Mg C ha⁻¹ yr⁻¹ across sites, reflected soil respiration driven by crop growth and disturbance, while methane fluxes were small and soils generally acted as weak sinks. Consequently, total greenhouse gas balances (nitrous oxide and methane) were dominated by nitrous oxide and shaped by management practices specific to site and crop phase, highlighting the need to minimise excess mineral nitrogen while sustaining productivity.

1. Introduction

Agriculture is a major contributor to anthropogenic greenhouse gas (GHG) emissions, accounting for approximately 10–12% of global emissions, while the broader Agriculture, Forestry and Other Land Use sector contributes about 22–24% (IPCC, 2022). Nitrous oxide (N₂O), methane (CH₄), and carbon dioxide (CO₂) are the principal gases exchanged between agroecosystems and the atmosphere, driven by interacting soil biological and chemical processes and management practices (Butterbach-Bahl et al., 2013). Among these, nitrous oxide is

particularly important due to its high global warming potential (273 times higher than carbon dioxide over 100 years) and its strong link to nitrogen inputs and microbial transformations in soils (Armour et al., 2021). Methane fluxes are primarily governed by soil redox conditions, with well-aerated soils often acting as a methane sink (Le Mer and Roger, 2001), while carbon dioxide emissions largely reflect heterotrophic respiration and soil organic carbon (SOC) turnover (Smith et al., 2018). Together, these gases provide key indicators of ecosystem functioning and management impacts on climate.

Reducing greenhouse gas emissions while maintaining agricultural

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productivity remains a central challenge for climate-smart agriculture and European climate policy targets (López-Santiago et al., 2024). In intensively managed systems, high nitrogen inputs and soil nitrogen surpluses often result in low nitrogen use efficiency and increased gaseous and leaching losses (Leip et al., 2014; Motasim et al., 2024). In Germany, agricultural soils are the dominant source of nitrous oxide emissions, accounting for approximately 75% of sectoral emissions (Rösemann et al., 2021). Addressing this challenge requires a process-based understanding of how long-term management practices interact with soil properties and environmental drivers to regulate greenhouse gas fluxes and nutrient cycling.

Long-term field experiments provide essential evidence for evaluating the cumulative and legacy effects of management on soil fertility, crop performance, and greenhouse gas emissions. Unlike short-term studies, long-term experiments capture slow-changing processes such as carbon sequestration, nutrient accumulation, and microbial carbon and nitrogen cycling that emerge from long-term interactions among management, plant inputs, and soil microbial communities (Ashraf et al., 2023; Jiang et al., 2024; Poeplau and Don, 2015; Rocci et al., 2024; Skadell et al., 2023). Despite their importance, many studies remain confined to single sites or short observation periods, limiting the ability to generalise across contrasting pedoclimatic conditions and management intensities (Lehmann et al., 2020b; Liao et al., 2024).

Fertilisation strategies are among the most influential management drivers of greenhouse gas emissions. Mineral fertilisers provide readily available nitrogen but often stimulate rapid nitrification and denitrification, increasing nitrous oxide emissions (Ravishankara et al., 2009). Organic amendments enhance soil organic carbon and microbial activity but may induce short-term emission peaks depending on substrate quality and environmental conditions (Möller and Müller, 2012; Valkama et al., 2024). Combined organic–mineral fertilisation systems can improve synchrony between nitrogen supply and crop demand, thereby enhancing productivity while reducing emissions (Darjee et al., 2024; Valkama et al., 2024). Long-term studies indicate that such systems can reduce nitrous oxide emissions while maintaining yields, highlighting their potential as climate-smart strategies.

Cover crops further influence soil carbon and nitrogen dynamics by enhancing soil carbon stabilisation, aggregate formation, and microbial activity (Ashraf et al., 2026; Gentsch et al., 2024; Hu et al., 2023, 2024; Xue et al., 2024). They can reduce nitrate leaching and improve nutrient retention, but may also increase short-term nitrous oxide emissions following residue incorporation due to enhanced microbial activity and carbon–nitrogen interactions (Abdalla et al., 2019; Basche et al., 2014; Bodner et al., 2018; Hansen et al., 2019; Helfrich et al., 2024). Their mitigation potential remains highly location-dependent, being strongly modulated by soil texture, hydrological conditions, and nutrient availability, which regulate gas diffusivity and microbial processes (Skinner, et al., 2014).

Soil properties such as texture, organic carbon content, and aeration strongly mediate these responses. Fine-textured soils tend to promote denitrification due to reduced gas diffusivity and greater water retention, while coarse-textured soils favour methane oxidation and are often associated with lower nitrous oxide emissions due to improved aeration (Skinner, et al., 2014). Soil moisture is also a key regulator, as it creates transient anaerobic microsites that stimulate nitrous oxide and methane production (Smith et al., 2018). These interactions highlight that greenhouse gas emissions are inherently context-dependent, which emerge from the interplay between management practices and site-specific soil and climatic conditions.

Because the processes governing nitrous oxide, methane, and carbon dioxide fluxes are interconnected, integrated metrics are required to assess overall climate performance. Expressing emissions as carbon dioxide equivalents (CO₂-eq) and normalising them to crop yield (yield-scaled emission intensity) provides a robust framework for evaluating trade-offs between productivity and environmental impact (Sainju et al., 2024; Snyder et al., 2009; van Groenigen et al., 2010). In this study,

climate efficiency was defined as the capacity of a cropping system to produce agricultural output while minimising associated trace gas fluxes. Operationally, it was assessed using yield-scaled emission intensity, a practical and widely adopted proxy for comparing systems with differing productivity levels. While yield-scaled emissions capture a central dimension of climate performance, the concept also encompasses broader system attributes, including resource use efficiency, nutrient cycling, and the capacity to sustain productivity under varying environmental conditions.

Against this background, this study aimed to quantify and compare greenhouse gas fluxes and climate-related efficiency across contrasting long-term agricultural systems. Using three long-term experimental sites in Germany, we assessed crop productivity alongside nitrous oxide, carbon dioxide, and methane fluxes, and derived both area- and yield-scaled emission intensities under different nutrient management strategies. We hypothesised that: (i) greenhouse gas emissions are primarily controlled by site conditions and crop phase, with nutrient management effects emerging most clearly for nitrous oxide during periods of high biological activity; (ii) carbon dioxide fluxes are mainly driven by temperature and soil disturbance; (iii) methane exchange remains small and near neutral; and (iv) yield-scaled emission intensities reflect differences in system productivity.

2. Materials and methods

2.1. Study sites and experimental design

This study was conducted at three long-term field experimental sites in Germany with different site conditions and long-term agricultural management (Table 1; Fig. 1). All three sites are characterised by silt-rich soils, with loess layers of about 50 cm over glaciofluvial sand at Asendorf, 1–1.3 m over sand at Dikopshof, and > 5 m at Frankenhausen over clay. The trial at Asendorf represents a conventionally managed low-input silage maize system with diverse cover crops; the trial at Dikopshof comprises Persian clover and winter rye managed conventionally under mineral, organic, and combined fertilisation regimes; and the trial at Frankenhausen includes potatoes managed with contrasting organic nutrient sources under the rules of the EU regulation on Organic farming. The three sites are briefly described below, and details on fertilisation management can be found in (Gentsch et al., 2024), (Seidel et al., 2021) and Möller et al. (2026). All tillage and fertilisation measures carried out during the gas measurement period are documented below. Sowing and harvest dates, trace gas sampling period, fertiliser amounts and types, and further information are provided in Table 2.

2.2. Asendorf (Lower Saxony)

The Asendorf site (52°45′ 48.4″ N, 9° 01′ 24.3″ E; 49 m a.s.l.) is located ~70 km north of Hannover, Germany. The climate is temperate oceanic, with a mean annual precipitation of ~778 mm and a mean annual temperature of ~9.4 °C. The soil developed from a shallow loess layer over glaciofluvial sand and is classified as a Stagnic Cambisol (IUSS Working Group WRB, 2022). Prior to the establishment of the long-term experiment, the site was managed as grassland until 2000 and subsequently converted to arable use under conservation tillage with initially low soil fertility and organic matter content. At the start of the CATCHY experiment in 2015, soils were characterised by relatively low organic carbon, reflecting previous management. Since then, management practices including straw incorporation, cover cropping, and combined organic and mineral fertilisation have contributed to gradual increases in soil carbon across most treatments. These developments indicate ongoing soil recovery and the importance of long-term management practices for rebuilding soil fertility and stabilising system performance over time (Gentsch et al., 2020, 2022, 2024).

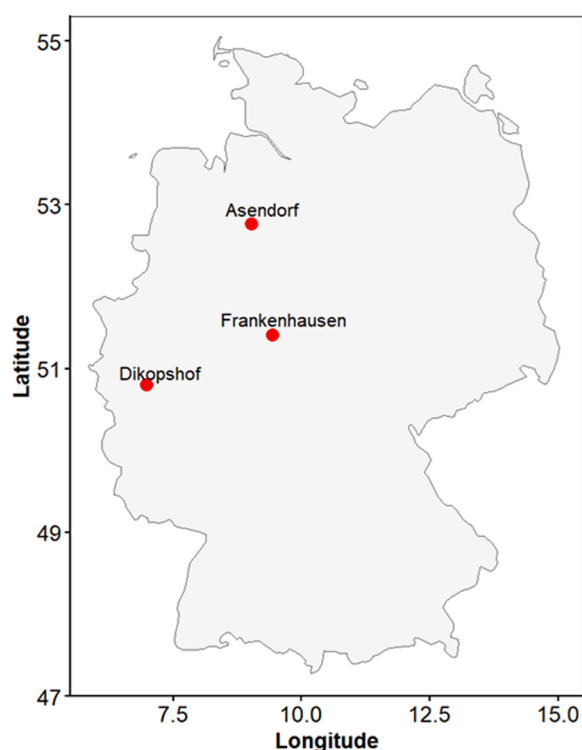
The CATCHY cover-crop experiment (established in 2015; Gentsch et al., 2024) is embedded in a conventional winter wheat–silage maize

Table 1

Summary of study sites, soil and climate characteristics. The soil characteristics refer to the topsoil (0–30 cm soil depth).

Site/ Location (Lat/Long)	Soil Type	Soil depth cm	Clay %	Silt	Sand	SOC	TN	Soil bulk density g cm ⁻³	Soil pH	CECeff cmol kg ⁻¹	Annual Precipitation mm	Mean Annual Temperature °C
Asendorf	Stagnic Cambisol	0–30	6.9	51.4	40.0	1.62	0.15	1.3	6.0–6.4	32.9	778	9.4
52° 45' 48.4" N 9° 01' 24.3" E		30–60	6.5	67.8	25.4	0.78	0.07	1.6	6.4	23.2		
Dikopshof	Haplic Luvisol	60–90	-	-	-	0.13	0.02	1.4	6.0	31.3		
50° 48' 21" N, 6° 59' 9" E,		0–30	16.7	69.6	13.7	1.60	0.08–0.14	1.4	5.8–6.7	-	671	11.1
		30–60	24.5	68.1	7.4	0.58	-	1.5	4.5	-		
Frankenhausen	Haplic Luvisol	60–90	19.1	36.7	44.2	0.46	-	1.6	4.6	-		
51° 24' 35.4" N, 9° 26' 03.2" E		0–30	18.6	79.9	1.6	1.12	0.12	1.5	6.7–7.2	14.4	699	9.4
		30–60	21.2	77.6	1.2	0.64	0.07	1.6	-	-		
		60–90	24.6	74.6	0.8	0.22	0.03	-	-	-		

SOC= soil organic carbon; TN= total nitrogen; CECeff= effective cation exchange capacity; N/A = not available; Long-term average weather (1991–2020)

**Fig. 1.** Location of the experiments.

rotation and comprises seven treatments: Fallow (no cover crop), mustard (*Sinapis alba* L.), Phacelia (*Phacelia tanacetifolia* Benth.), bristle oat (*Avena strigosa* Schreb.), Egyptian clover (*Trifolium alexandrinum* L.), Mix4 (a four-species mixture consisting of the above single species), and Mix12 (a 12-species mixture including *Pisum sativum*, *Sorghum bicolor*, *Phacelia tanacetifolia*, *Linum usitatissimum*, *Vicia pannonica*, *Raphanus sativus*, *Guizotia abyssinica*, *Helianthus annuus*, *Camelina sativa*, *Trifolium resupinatum*, *Trifolium hybridum*, and *Trifolium incarnatum*; see [Supplementary Table S1](#)). Treatments were arranged in a randomised complete block design with three replicates. During the monitored rotation, winter wheat straw was retained and incorporated to a depth of ~15 cm. Cover crops were sown on 10 August 2023 and maintained through autumn and winter, then terminated and incorporated in late spring 2024 before maize sowing. Maize was fertilised after sowing (see [Table 2](#)) and harvested in October 2024, after which winter wheat was sown in late 2024. The mineral fertilisation was applied using liquid

ammonium nitrate (pH 6–7) via injection. The chambers (pipes, see below) for the gas measurements remained in place during the fertilisation. Gas emission measurements considered here were conducted from mid-October 2023 to mid-October 2024. This design enabled assessment of how cover-crop identity and cover crop diversity influence nitrogen cycling and emissions of high-silt soils with relatively high nutrient availability ([Table 1](#)).

2.3. Dikopshof (North Rhine–Westphalia)

The Dikopshof long-term experiment, established in 1904 (50° 48' 21" N, 6° 59' 9" E; 61 m a.s.l.), is located within an Atlantic climate region. Long-term climate conditions, based on 30-year averages (1991–2020) from the nearest meteorological station, indicate a mean annual temperature of 11.1 °C and an annual precipitation of 671 mm. The soil is classified as a Haplic Luvisol derived from loess over sand, characterised by a silty loam topsoil and a clay-enriched Bt horizon ([Seidel et al., 2021](#)). At the start of the experiment, soils were relatively homogeneous and moderately fertile, reflecting the inherent properties of the loess-derived parent material prior to long-term differentiation through fertilisation management. Over more than a century of continuous management, contrasting fertilisation regimes have led to pronounced differences in soil fertility and system performance. At Dikopshof, topsoil organic carbon concentrations were approximately 1.0% in the mid-1980s and increased slightly to around 1.1% under balanced mineral fertilisation with liming ([Seidel et al., 2021](#)). Similarly, dissolved P concentrations increased from initial values of approximately 0.0015–0.002% to about 0.003–0.004% under balanced fertilisation. Relative yields remained comparatively stable over time (approximately 90–95% initially vs. 88–92% by the end of 2018), indicating that long-term balanced fertilisation sustained productivity. These long-term trajectories demonstrate the long-term effects of fertilisation on soil function and provide a robust basis for evaluating management impacts on greenhouse gas dynamics and agroecosystem performance.

The site follows a five-year crop rotation, including sugar beet, winter wheat, winter rye, fodder legume and potato without cover crops. Each crop was grown annually on one of five permanent strips (A–E), with each strip comprising 24 fertilisation treatments. From the full treatment matrix, we selected seven contrasting fertilisation strategies that represent key nutrient management gradients, including complete mineral fertilisation, nutrient omission, liming effects, and organic nutrient inputs via cattle farmyard manure (+m) ([Table 2](#)). The selected treatments were: complete mineral fertilisation with liming (NPKCa); complete mineral fertilisation without liming (NPK₋) to assess liming effects; integrated mineral–organic fertilisation with liming and supplemental mineral nitrogen (NPKCa+m+s); manure-only

Table 2

Summary of management focus, crops assessed, nutrient sources, key management variants, and total nitrogen inputs across the three LTE sites.

Site	Crop monitored	GHG sampling ¹	Treatments	N ²	P	K	CaO ⁴	Fertiliser/nutrient Sources
	Crop (cultivar) (sown – harvested/ ploughed)			Application rate (kg ha ⁻¹ yr ⁻¹) ³				
Frankenhausen	Potatoes (Lea)	03.19.2024	VF_CC	20	1.4	25		Tofu residues and
	Organic systems	05.03.2024 –	MF_2.0	20	2.8	25		fresh clover-grass mulch
	compared (with and	09.20.2024	SF_GWC	72	12.4	186		Manure compost
	without livestock)			53	7.8	37		Clover-grass compost
Dikopshof	Winter rye	10.11.2024	NPK_	40/0	22/	83/	0/0	Mineral fertilisers: Calcium ammonium nitrate, triple
	(Tayo)	–10.10.2025	NPKCa,	40/0	31	116	0/	superphosphate (45%), burnt lime (90% CaO).
	Fertiliser type/nutrient	11.04.2023 –	NPKCa+m+s,	120/	22/	83/	1143	Organic fertiliser from farm yard manure (cattle)
	replacement effects	07.31.2024	m,	0	31	116	0/	
	Persian clover	04.29.2025	_PKCa,	40/0	75/	282/	1143	
	(Passat)		_PKCa+m,	0/0	31	116	0/0	
	05.15.2024 –		unfertilised	40/0	22/	83/0	0/	
	03.06.2025			0/0	0	116/	1143	
					31/	116	0/	
					31	199/	1143	
Asendorf	Various catch	10.12.2023 –	Clover,	145	69	120	139	Potassium fertiliser with magnesium and sulphur (40%
	crops	10.10.2024	Mustard,					K ₂ O / 6% MgO / 5% S), Diammonium phosphate (DAP,
	08.10.2023 –		Phacelia,					18% N / 46% P ₂ O ₅), Granulated lime with sulphur,
	Maize (Crosbey)		Mix4,					Nitrogen–sulphur fertiliser (25% N / 6% S)
	05.16.2024 –		Mix12,					
	10.10.2024		Oat,					
			Fallow					

¹ GHG sampling refers to the period considered for calculating annual cumulative emissions.² N applied in the case of organic amendments (slurry, farmyard manure, tofu residues, compost) refers to total N.³ At Dikopshof, application rate refers to winter rye/Persian clover; N from mineral fertiliser or farm-yard manure was applied only to winter rye, while P, K, and CaO were applied to Persian clover.⁴ At Frankenhausen, CaO was applied in the form of burnt lime.Abbreviations: VF_CC = vegan-organic system without livestock; MF_2.0 = mixed crop–livestock system (2 LU ha⁻¹ yr⁻¹); SF_GWC = soil fertility–focused system with green waste compost; m = manure; s = supplemental N; Mix4/Mix12 = 4- or 12-species catch crop mixtures (see [supplementary material](#) for details).

fertilisation (m); phosphorus–potassium–calcium fertilisation without nitrogen (_PKCa) to assess nitrogen omission under limed conditions; phosphorus–potassium–calcium fertilisation with manure (_PKCa+m); and an unfertilised control (without mineral nutrients or organic inputs). These treatments allowed separation of the effects of mineral nitrogen supply, liming (calcium addition, Ca), organic nutrient inputs, and their interactions on crop productivity and greenhouse gas emissions under long-term contrasting fertilisation regimes (Table 2). The trial at Dikopshof lacks replicated plots because of its early establishment. Thus, replicates in this study refer to within-plot replicates.

Farmyard cattle manure was applied (~12 t ha⁻¹ yr⁻¹) to winter rye and sugar beet, while mineral fertilisation regimes remained consistent over decades. Winter rye (grown after winter wheat) and Persian clover (grown after winter rye) were monitored in 2024/2025, with gas emission measurements considered here from May 2024 to May 2025 (Persian clover) and October 2024 to October 2025 (winter rye). The Persian clover phase started with ploughing and sowing in late May/early June 2024. In November 2024, the clover plots received mineral P and K fertilisers and burnt lime (90% CaO), with amounts varying by treatment (Table 2). The clover phase was then terminated in early spring 2025 by ploughing the clover biomass into the soil in March 2025, marking the transition to the subsequent potato crop, which was planted in May 2025. Following the winter wheat harvest in summer 2024, the manure-based treatments (i.e., m, _PKCa+m, and NPKCa+m+s) received cattle farmyard manure in addition to mineral fertilisers where applicable. Winter rye plots received farmyard manure on October 29th, 2024. The plots were subsequently ploughed to prepare the seedbed, and winter rye was sown shortly thereafter. During the following growing season, chemical plant protection and additional mineral nitrogen fertilisation were applied in spring/early summer

2025, and the crop was harvested in late summer 2025. During mineral fertiliser application, the gas-measurement chambers were temporarily closed, and the corresponding fertiliser amounts were applied manually within the chamber area. The chambers were removed prior to tillage operations and reinstalled immediately afterwards.

2.4. Frankenhausen (Hesse)

The Frankenhausen experiment site (51° 24′35.4″N, 9° 26′03.2″E; 220 m a.s.l.), located in central Germany, is characterised by a warm-temperate humid climate, with mean annual temperature of 9.4 °C and annual precipitation of 699 mm for the 1991–2020 reference period. The soil is classified as a Haplic Luvisol with very high silt content (Table 1). The site has been managed organically since 1998 under diverse crop rotations dominated by legumes and forage crops. At the start of the trial in 2017, soils were characterised by moderate fertility, reflecting long-term low-input management and biologically driven nutrient cycling. Although no century-scale baseline data are available, initial organic carbon measurements from 2018 provide an important reference for assessing early soil fertility dynamics (Möller et al., 2026). Over the first five years, soil organic carbon remained stable or increased slightly across most treatments, with significant increases observed under systems receiving high organic matter inputs. These patterns indicate that current management practices can maintain or enhance soil carbon stocks, particularly in systems integrating legume–grass mixtures. In the current study, three systems were investigated: i.) a *vegan cut and carry* system (using the clover–grass grown in the crop rotation as fertiliser by transferring it from the clover–grass field to a field with a nutrient-demanding crop, here: potato) without livestock and a high share of root crops in the rotation (VF–CC), ii.) a soil

fertility-focused system without livestock emphasising *green waste compost* and cover crops (SF–GWC), and iii.) a livestock-integrated *mixed farming* system with 50% legume crops (MF2.0). These systems differed in crop rotation and in organic amendments (clover grass mulch and tofu residues, green waste compost, or cattle manure and slurry) (Möller et al., 2026). The experimental layout followed a split-plot design with four replicates.

After spring ploughing, each system received its system-specific organic fertilisation before planting (VF–CC: plant-based inputs, including Tofu whey and fresh clover grass mulch; MF2.0: livestock-derived amendments, i.e., composted manure; SF–GWC: compost-based inputs; see Table 2). Potatoes were then planted and ridges were formed, followed by repeated mechanical weed control and soil loosening operations (e.g., harrowing/track loosening; flame weeding) and additional ridging/hilling during early growth. The crop was harvested in early autumn 2024, after which soils were cultivated using disc-harrowing and transitioned to the subsequent crop phase (e.g., winter wheat establishment in SF–GWC and MF2.0). During winter, management activities were limited to post-harvest soil management and preparation for the subsequent cropping phase (Table 2). Detailed management records and fertilisation protocols are provided by Möller et al. (2026). Gas emission measurements were conducted from March 2024 to March 2025.

2.5. Agronomic data collection

Agronomic data were collected during the 2023/2024 (Asendorf) and 2024/2025 (Dikopshof and Frankenhäusen trials) cropping seasons to quantify crop performance and nutrient uptake. Measurements included crop biomass, grain or tuber yield, aboveground residue inputs, and plant nitrogen content. Monthly biomass sampling was conducted only for Persian clover by harvesting 4 m of crop rows per plot. Fresh biomass was weighed in the field, and subsamples were collected for carbon and nitrogen analyses and dry-matter determination. Samples were oven-dried to constant weight at 60 °C, ground, and stored for laboratory analysis, with dry matter determined after drying at 105 °C for 24 h. Final crop yields for all systems were determined at harvest from central subplots to minimise border effects. At Frankenhäusen, potato yields were assessed as marketable tuber yield by excluding damaged and undersized tubers according to standard grading criteria. At the other sites, grain and forage yields were determined from harvested plot areas and expressed on a dry matter basis. Site-specific climatic variables, including daily air temperature, precipitation, and relative humidity, were obtained from on-site meteorological stations. Where data gaps occurred, records from the nearest German Meteorological Service station were used to complete the dataset.

2.6. Greenhouse gas flux measurements

Soil–atmosphere fluxes of nitrous oxide, carbon dioxide, and methane were measured using dynamic chambers coupled to portable gas analysers during measurement campaigns spanning the full cropping periods from sowing to harvest of the selected crops (Table 2). Measurements were performed weekly during the growing season and biweekly during the cold season (November–March). Following management events such as fertilisation and tillage, or freeze–thaw cycles, intensive monitoring was conducted on several consecutive days to capture emission peaks. At Dikopshof and Asendorf, gas concentrations were quantified using a Gasmet DX4040 Fourier-transform infra-red analyser (Gasmet Technologies, Finland). At Frankenhäusen, nitrous oxide and carbon dioxide fluxes were measured using a MIRA Ultra N₂O/CO₂ analyser, while methane fluxes were measured using a MIRA Ultra Mobile LDS CH₄/C₂H₆ analyser based on a laser absorption spectroscopy (AERIS Technologies, Inc., USA). Both instruments were connected via a PRI-8600D multiplexer (Pri-eco Technology Co., Ltd., China). At all sites, gas-measurement chambers were constructed from

polyvinyl chloride (PVC) sewage pipes (tubes), with a diameter of 20 cm and a height of 6 cm. The chamber bases were inserted approximately 5 cm into the soil between crop rows. Four chambers (pipes) were installed in close proximity and connected to the gas analysers via tubing for flux measurements (see Figure S1 in the Supplementary material). Each “chamber set”, consisting of four chambers was replicated three times. The chambers remained in place throughout the measurement period and were only removed when necessary, such as during tillage operations. Under dry conditions, chambers were gently inserted into the soil using a flat wooden board to minimise disturbance. Four pipes were connected to a four-in-one chamber with a total surface area of 0.0314 m² and a total headspace volume of 0.00572 m³. Chamber dimensions were incorporated into all flux calculations to ensure consistent conversion of gas-concentration changes into area-based emission rates.

At Frankenhäusen, both large and small static chambers were used to quantify methane and nitrous oxide fluxes in order to represent the ridge–furrow structure of the potato system. Small chambers installed between the ridges represented one-third of the surface area and were comparable to the setup at the two other sites. Large non-transparent PVC chambers (0.25 m² surface area, 0.16 m³ headspace volume) installed on the ridges represented the remaining two-thirds of the surface area. Fluxes were, therefore, calculated as an area-weighted combination of inter-row and ridge measurements (1/3 inter-row, 2/3 ridge). Carbon dioxide fluxes were initially measured using the large non-transparent chambers placed on the ridges until crop germination (28 May 2024) to capture soil respiration following tillage. After germination, carbon dioxide measurements were continued using the same standardised chamber design employed at the other sites, positioned between the ridges to ensure cross-site comparability while avoiding confounding effects of plant respiration. Each measurement lasted approximately 8–10 min, depending on the site and analyser type, with headspace gas concentrations recorded at 21-s intervals at Dikopshof, 60-s intervals at Asendorf, and 1-s intervals at Frankenhäusen.

In addition to trace gases, the analysers continuously recorded water vapour and atmospheric pressure, while air and chamber headspace temperature were monitored throughout each measurement. Fluxes were calculated from the linear change in gas concentration over time and corrected for chamber volume, surface area, air temperature, atmospheric pressure, and chamber water vapour (Rheault et al., 2024).

2.7. Data processing and statistical analysis

Gas fluxes were processed in R 4.3.2 (R Core Team, 2024) using the *goFlux* package (version 0.2.0; (Rheault et al., 2024), which is specifically designed for high-frequency chamber data and incorporates corrections for water vapour dilution.

Fluxes were calculated using the flux term:

$$\text{flux.term.gasfluxes} = \frac{VMP}{SRT} \quad (1)$$

where V is the total chamber volume (m³), M is the molar mass of the gas (mol), P is atmospheric pressure (Pa), S is the chamber footprint area (m²), R is the universal gas constant (8.314 J m³ Pa mol^{−1} K^{−1}), and T is chamber air temperature (K).

The *goFlux* workflow additionally corrects for water vapour dilution inside the chamber, expressed as:

$$\text{flux.term.goFlux} = \frac{(1 - H_2O)VP}{SRT} \quad (2)$$

where H_2O is the water vapour mole fraction.

Daily emissions were estimated by linear interpolation between measurement dates, and annual totals were obtained by integrating daily fluxes. Gaps ≥ 14 days were filled using adjacent fluxes within the same treatment. Emissions were expressed as area-based fluxes (kg ha^{−1}

year⁻¹), yield-scaled emissions (g GHG kg⁻¹ dry matter), and

total CO₂-equivalents (CO₂-eq), calculated using 100-year global warming potentials (GWP₁₀₀) following the definition of the (Intergovernmental Panel on Climate Change (IPCC), 2023):

$$CO_{2eq} = (N_2O - N \times 1.57 \times 273) + (CH_4 - C \times 27) \quad (3)$$

where N₂O and CH₄ represent cumulative N- or C-based fluxes of each gas (area-based), and the coefficients converting them to CO₂-equivalents. Carbon dioxide fluxes were analysed separately as indicators of soil respiration and were not included in CO₂-equivalent calculations because they primarily reflect short-term biogenic carbon cycling rather than net ecosystem carbon balance.

All statistical analyses were conducted separately for each site and crop phase. Treatment effects on crop yield, cumulative greenhouse gas emissions, and yield-scaled indicators were analysed using linear mixed-effects models fitted with the *lme* function in the *nlme* package in R. Treatment was specified as a fixed effect, and replicate was included as a random intercept. To account for heterogeneity of variance among treatments, a *varIdent* variance structure was applied, allowing treatment-specific residual variances. Models were fitted using restricted maximum likelihood (REML). The significance of treatment effects was assessed by ANOVA of the fitted models. Model assumptions were checked graphically using residual-fitted and normal Q-Q plots. Estimated marginal means were calculated with the *emmeans* package, and Tukey-adjusted pairwise comparisons were used to separate treatment means. Compact letter displays were generated to summarise

homogeneous groups at the 5% significance level.

All analyses were performed in R version 4.3.2. (R Core Team, 2024). At the Dikopshof site, the long-term fertilisation experiment follows a historical design established in 1904 and does not include true field-scale replication of treatments. Consequently, statistical analyses were based on repeated measurements within plots (e.g. chamber positions and temporal observations), which were treated as the experimental unit. While this approach allows for the assessment of temporal dynamics and within-plot variability, it does not provide independent replication at the treatment level. Therefore, the statistical inference for Dikopshof is restricted to comparisons within the experimental layout rather than fully independent treatment effects. Accordingly, the compact letter displays presented for Dikopshof are intended to support interpretation of relative within-experiment contrasts and temporal dynamics, rather than inferential treatment comparisons in a fully replicated experimental design.

3. Results

3.1. Crop yield responses across sites

Dry matter yields differed clearly among sites and management systems due to the different crops involved (Fig. 2). At Asendorf, silage maize grown in 2024 showed only minor yield variation among cover-crop and fallow treatments, ranging from 18.4 ± 0.9–19.7 ± 0.4 Mg DM ha⁻¹ yr⁻¹. The Oat treatment produced the highest yield (19.74

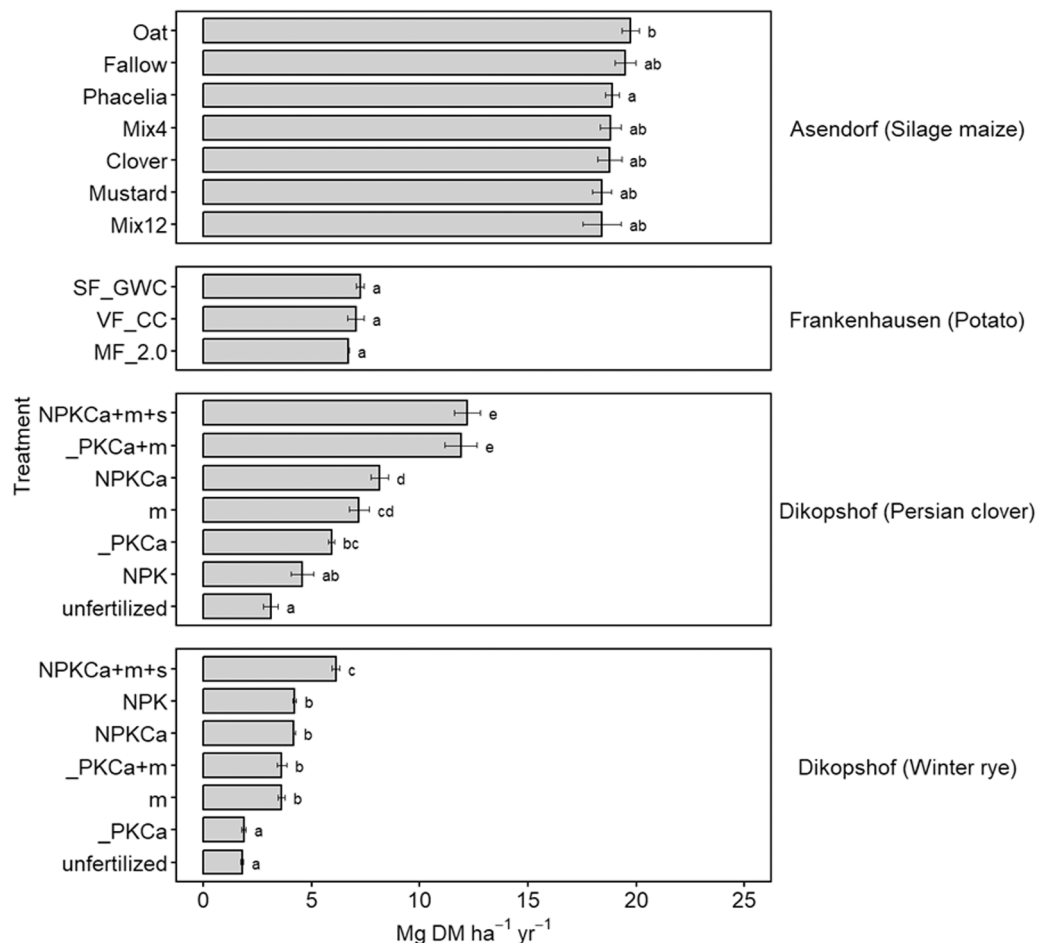


Fig. 2. Average crop yield (dry mass) in 2024/25 cropping season as affected by catch crop type (Asendorf: silage maize), nutrient replacement (Dikopshof: Persian clover - sum of 4 harvests; winter rye) and organic management strategies (Frankenhausen: potato tubers). Error bars represent the standard error of the mean; different letters indicate significant differences at $P < 0.05$ (Tukey). For Dikopshof, compact letter displays are based on repeated within-plot measurements. As the historical design lacks independent field-scale replication, treatment differences should be interpreted cautiously.

± 0.41), while Mix12 (18.40 ± 0.89) and Mustard (18.42 ± 0.44 t DM ha^{-1}) showed the lowest values. Maize yield under Phacelia treatment (18.90 ± 0.33) was significantly lower than Oat ($P < 0.05$), whereas Mix12, Mustard, Clover (18.75 ± 0.56), Mix4 (18.82 ± 0.49), and Fallow (19.51 ± 0.48 t DM ha^{-1}) did not differ significantly from either treatment ($P > 0.05$). At Frankenhausen, marketable potato yields were similarly homogeneous, ranging from 6.7 ± 0.04 – 7.3 ± 0.2 Mg DM $\text{ha}^{-1} \text{yr}^{-1}$. The compost-based organic system produced the highest yields (about 8% higher than the mixed farming system and ~3% higher than the vegan cut-and-carry system), but these differences were not statistically significant ($P > 0.05$).

In contrast, yields at Dikopshof differed among fertilisation treatments. During the Persian clover phase, cumulative dry matter yields

(sum of four cuts) ranged from 3.12 ± 0.34 in the unfertilised control to 12.20 ± 0.60 Mg DM ha^{-1} under combined mineral–organic fertilisation with liming (NPKCa+m+s). The highest yields were observed in the manure + PK with lime treatment (_PKCa+m; 11.91 ± 0.74) and NPKCa+m+s (12.20 ± 0.60 Mg DM ha^{-1}), which did not differ significantly from each other. The complete mineral fertilisation with lime treatment (NPKCa; 8.16 ± 0.40) and manure-only (m; 7.19 ± 0.46 Mg DM ha^{-1}) formed intermediate yield groups. Lower yields were observed under nitrogen-omission treatment (_PKCa; 5.92 ± 0.13) and the complete mineral fertilisation without lime (NPK; 4.56 ± 0.52 Mg DM ha^{-1}), while the unfertilised control showed the lowest yield. Yield under NPKCa was significantly higher than under NPK_ and _PKCa ($P < 0.05$). The treatment _PKCa+m produced significantly higher yields than both

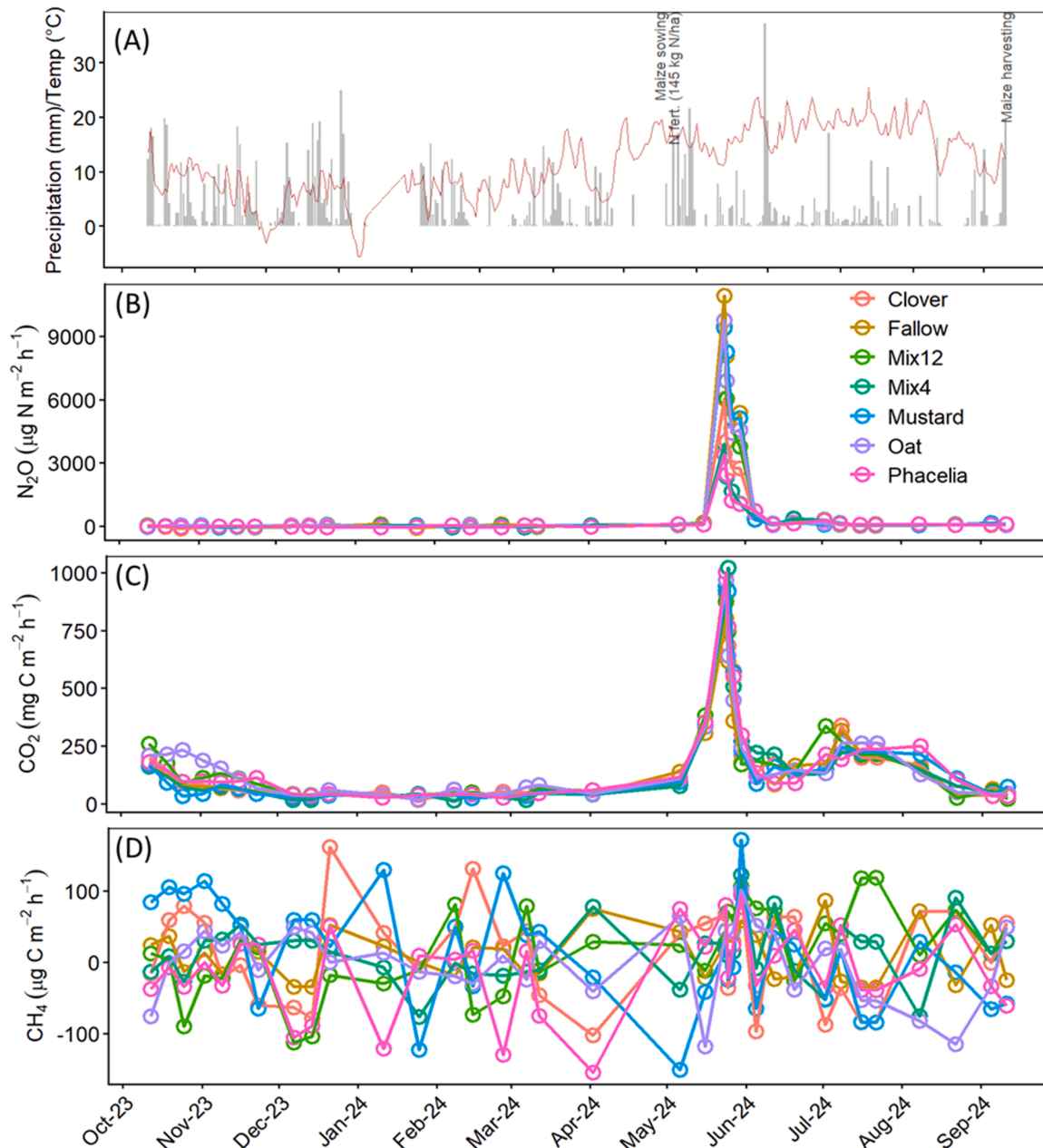


Fig. 3. Effects of catch crop treatments and management activities on greenhouse-gas fluxes at Asendorf. Panel (A) shows precipitation and temperature dynamics, with grey bars indicating daily precipitation and the brown line representing mean daily air temperature. Panels (B–D) show temporal dynamics of (B) N₂O–N, (C) CO₂–C, and (D) CH₄–C fluxes for the different catch crop treatments. Circles represent treatment-wise mean fluxes at each sampling date, calculated from replicate chamber measurements; lines connect successive sampling dates to illustrate temporal trends and do not imply interpolation between measurements. Vertical annotations in panel (A) indicate key management events (fertilisation and harvest). Catch crop was sown on August 10, 2023.

manure only and NPKCa treatments ($P < 0.05$).

Yield differences were also evident during the winter rye phase. Grain yields ranged from 1.80 ± 0.06 in the unfertilised control to 6.13 ± 0.18 Mg DM ha⁻¹ under NPKCa+m+s. Mineral NPK fertilisation with liming (NPKCa; 4.18 ± 0.07) or without lime (NPK; 4.20 ± 0.07) resulted in similar yields and did not differ significantly from manure-only (m; 3.59 ± 0.16) or _PKCa+m (3.62 ± 0.21 Mg DM ha⁻¹). The lowest yields were observed in _PKCa (1.87 ± 0.09) and the unfertilised control (1.80 ± 0.06 Mg DM ha⁻¹), which did not differ statistically from each other. NPKCa+m+s produced significantly higher yields than all other treatments ($P < 0.05$).

3.2. Weather–management interaction effects on greenhouse gas fluxes

Across all sites, gas fluxes were dominated by short-lived responses to management and weather events, whereas treatment differences were generally small outside peak emission periods (Figs. 3–6). For improved conciseness, detailed temporal dynamics and event-specific flux patterns are provided in the [Supplementary Material](#) (Text S1). At Asendorf, flux dynamics were primarily driven by mineral N fertilisation and seasonal climate (Fig. 3). A pronounced nitrous oxide peak occurred following fertiliser application under warm and moist conditions, with fluxes reaching approximately 300–10,000 $\mu\text{g N m}^{-2} \text{h}^{-1}$ (Fig. 3A–B), whereas emissions remained low outside this period. Differences among cover-crop treatments were minor and mainly evident during this peak, with

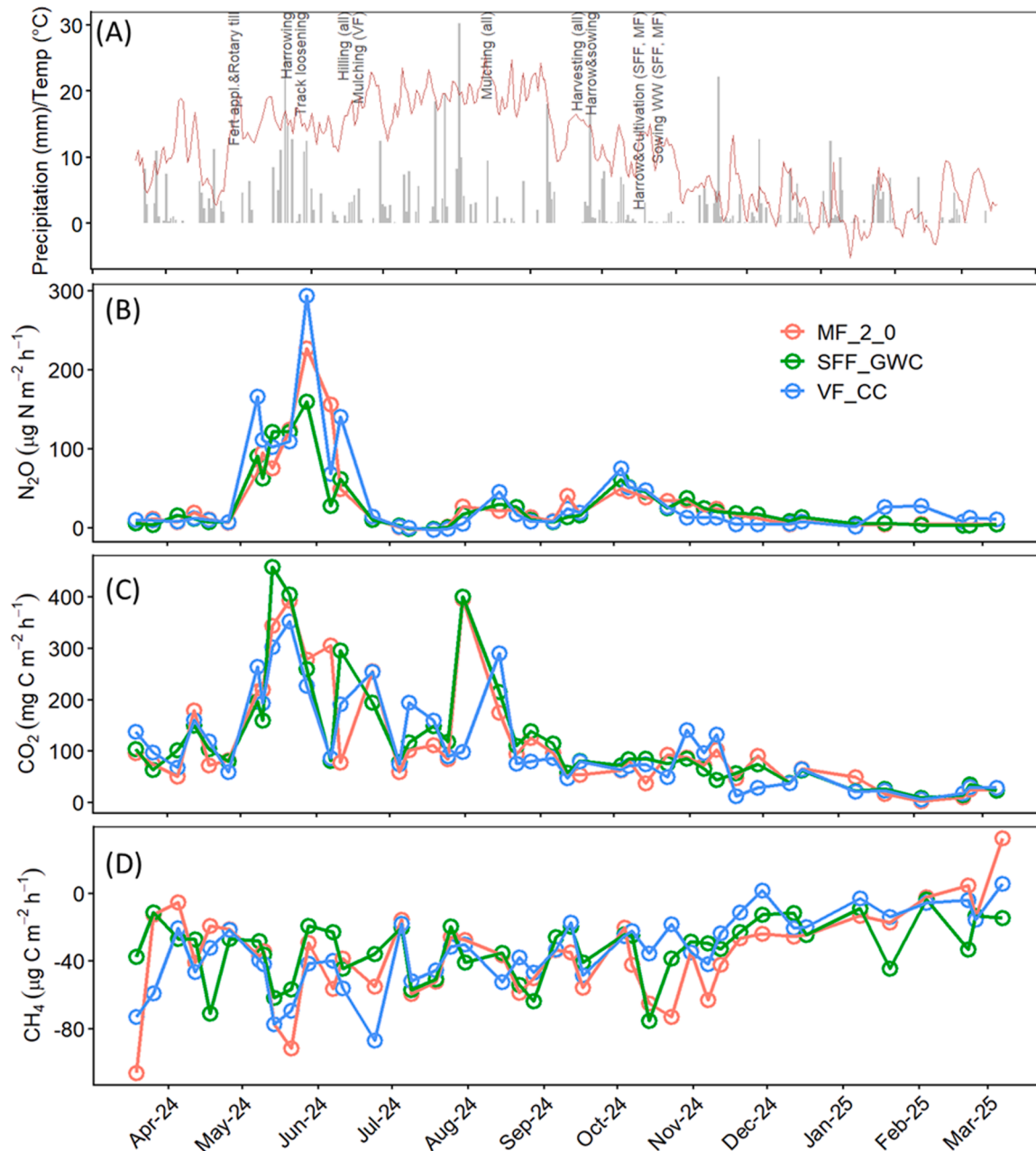


Fig. 4. Effects of organic crop rotations and potato management activities on greenhouse-gas fluxes at Frankenhausen. Panel (A) shows precipitation and temperature dynamics, with grey bars indicating daily precipitation and the brown line representing mean daily air temperature; harrowing and ridge cultivation were conducted three days after organic manure application. Panels (B–D) depict temporal dynamics of (B) N₂O–N, (C) CO₂–C, and (D) CH₄–C fluxes. Circles represent treatment-wise mean fluxes at each sampling date, calculated from replicate chamber measurements, while lines connect successive sampling dates to visualise temporal trends without implying interpolation.

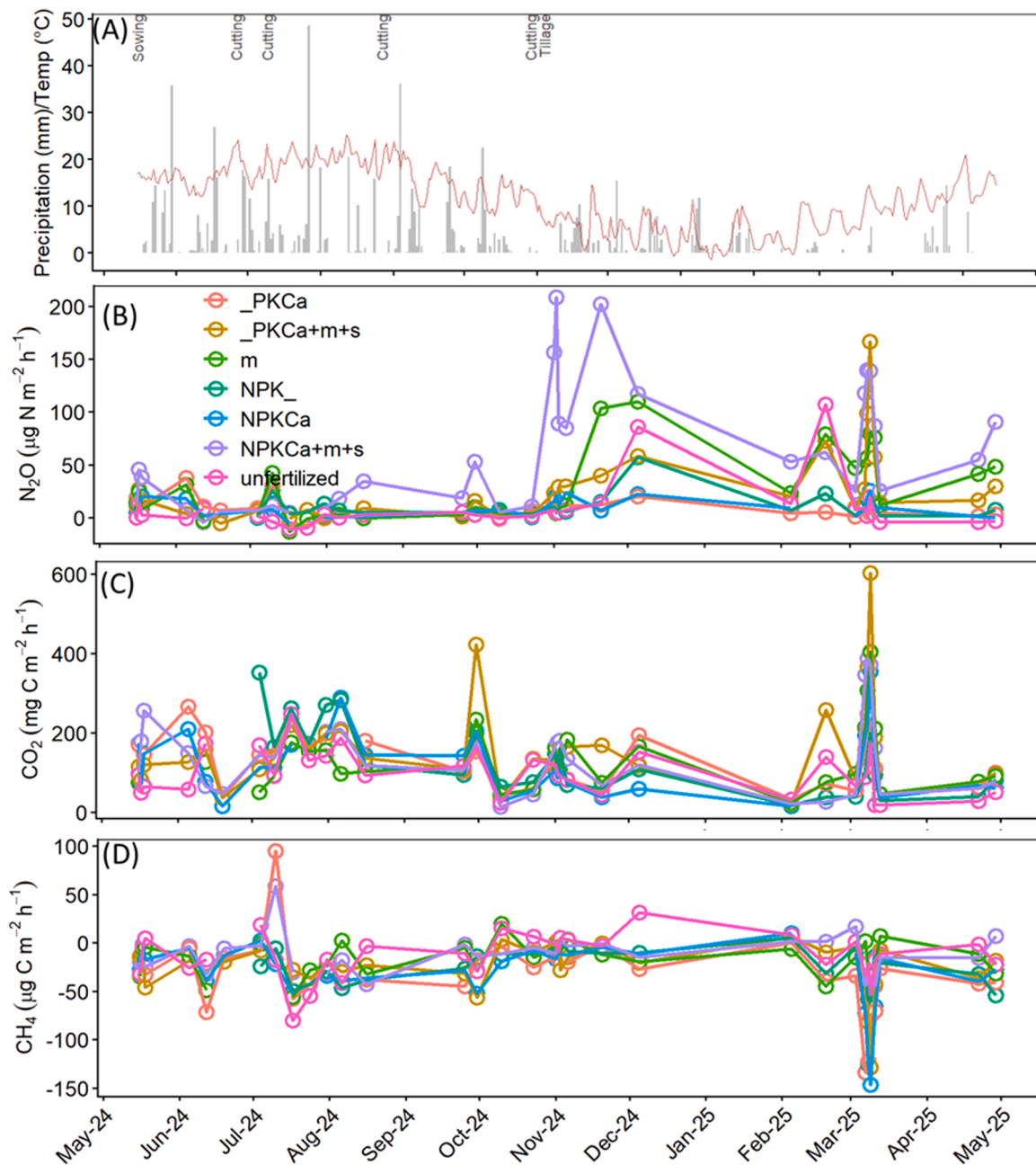


Fig. 5. Effects of different soil nutrient replacement treatments during the Persian clover phase within a crop rotation sequence at Dikopshof. Panel (A) shows associated weather dynamics and management activities, with grey bars indicating daily precipitation and the brown line representing mean daily air temperature. Panels (B–D) depict temporal dynamics of (B) N_2O –N, (C) CO_2 –C, and (D) CH_4 –C fluxes. Circles represent treatment-wise mean fluxes at each sampling date, calculated from replicate chamber measurements, while lines connect successive sampling dates to visualise temporal trends without implying interpolation.

generally higher emissions under fallow and lower emissions under mixed and single-species cover crops (Fig. 3; Fig. S2). Carbon dioxide fluxes followed clear seasonal temperature patterns, increasing from winter minima to summer maxima (≈ 800 – $1000 \text{ mg C m}^{-2} \text{h}^{-1}$), and largely overlapped among treatments (Fig. 3C). Methane exchange remained close to zero throughout (Fig. 3D).

At Frankenhausen, gas fluxes were highly episodic and closely linked to fertilisation, soil disturbance, and rainfall-driven soil moisture pulses (Fig. 4). Nitrous oxide emissions showed short-lived peaks, typically ranging from < 50 under baseline conditions to > 300 – $400 \text{ } \mu\text{g N m}^{-2} \text{h}^{-1}$ during peak events, with highest responses in the vegan cut-and-carry system and lowest in compost-based organic system (Fig. 4B). Carbon dioxide fluxes followed crop development and seasonal temperature dynamics, with peaks during active growth phases and soil

disturbance (Fig. 4C). In contrast, methane exchange was predominantly negative, generally ranging from approximately -90 – $0 \text{ } \mu\text{g C m}^{-2} \text{h}^{-1}$, indicating that this site functioned as a net methane sink (Fig. 4D).

At Dikopshof (clover phase), nitrous oxide and carbon dioxide fluxes were strongly event-driven, with peaks following fertilisation, cutting, residue incorporation, and freeze–thaw events (Fig. 5). Baseline nitrous oxide emissions were generally low (< 20 – 40), but increased to approximately 100 – $200 \text{ } \mu\text{g N m}^{-2} \text{h}^{-1}$ during management events, particularly in manure and combined fertilisation treatments (Fig. 5B). Carbon dioxide fluxes increased following disturbance, reaching approximately 400 – $600 \text{ mg C m}^{-2} \text{h}^{-1}$, while otherwise following seasonal trends (Fig. 5C). Methane exchange remained small and near neutral, typically ranging between -80 and $+ 80 \text{ } \mu\text{g C m}^{-2} \text{h}^{-1}$ (Fig. 5D).

During the winter rye phase, nitrous oxide emissions were generally

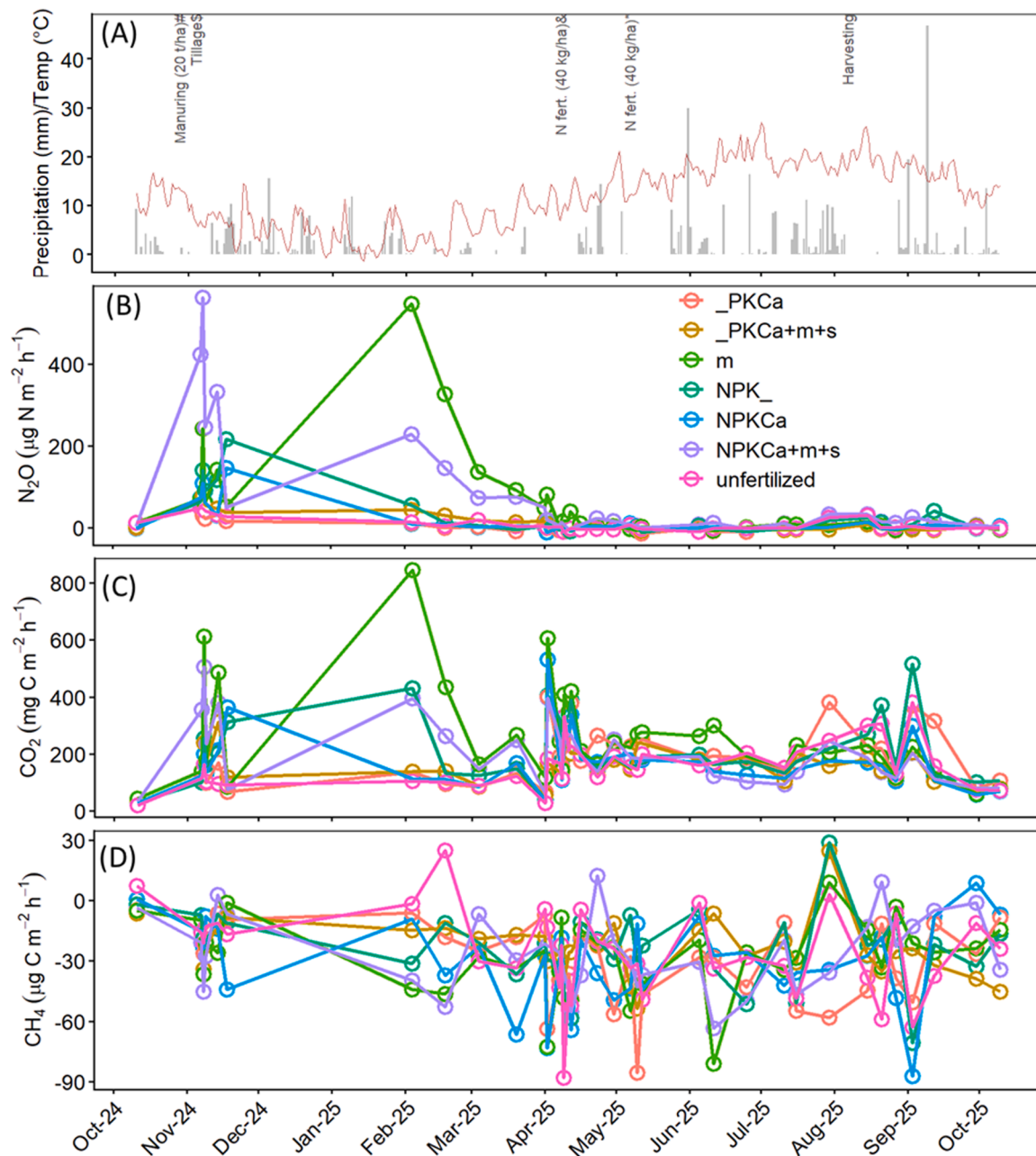


Fig. 6. Effects of different soil nutrient replacement treatments during the winter rye phase within a crop rotation sequence at Dikopshof. Panel (A) shows associated weather dynamics and management activities, with grey bars indicating daily precipitation and the brown line representing mean daily air temperature. Panels (B–D) depict temporal dynamics of (B) N_2O-N , (C) CO_2-C , and (D) CH_4-C fluxes. Circles represent treatment-wise mean fluxes at each sampling date, calculated from replicate chamber measurements, while lines connect successive sampling dates to visualise temporal trends without implying interpolation. Management annotations indicate fertilisation events: #farmyard manure applied to manure (m) treatments followed by cultivation after 3 days; *ammonium sulphate applied to all nitrogen (N) treatments; *ammonium sulphate applied to the NPKCa+m+s treatment.

low but showed pronounced peaks following fertilisation and freeze–thaw events (Fig. 6). Peak fluxes reached approximately 500–600 in manure and mineral N treatments, whereas N-omission treatments remained low (<50 – $70 \mu g N m^{-2} h^{-1}$) (Fig. 6B). Carbon dioxide fluxes reflected seasonal temperature variation and soil disturbance, with peaks of approximately 400–850 $mg C m^{-2} h^{-1}$, particularly in fertilised treatments (Fig. 6C). Methane fluxes remained close to zero across all treatments, generally ranging from -100 to $+50 \mu g C m^{-2} h^{-1}$, with no consistent treatment effects (Fig. 6D).

3.3. Treatment effects on annual greenhouse gas emissions

3.3.1. Nitrous oxide emissions

Across sites, crop phases, and nutrient strategies, area-scaled and yield-scaled annual nitrous oxide emissions varied by more than two orders of magnitude, with a consistent ranking among sites (Fig. 7A–B). Area-based emissions were highest for maize at Asendorf (10.8–26.8), intermediate for potatoes at Frankenhausen (2.22–2.54) and during the clover phase at Dikopshof (0.67–4.71), and lowest during the winter rye phase at Dikopshof (0.31–9.24 $kg N ha^{-1} yr^{-1}$). With respect to yield-scaled nitrous oxide emissions, some winter rye treatments at Dikopshof had higher emissions than silage maize treatments at Asendorf.

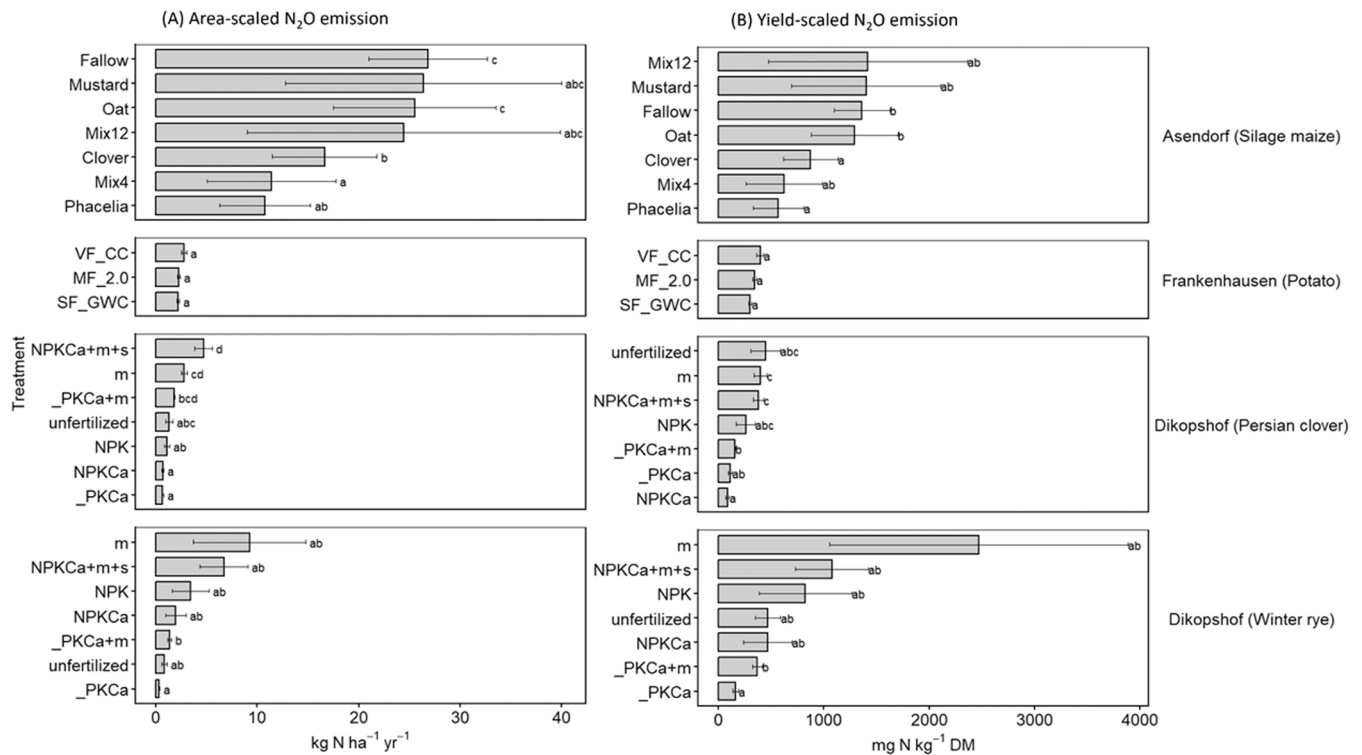


Fig. 7. Cumulative area-scaled N₂O-N fluxes (A) and product-scaled N₂O fluxes (B) from catch crop treatments (Asendorf), nutrient replacement treatments under Persian clover (DikopshofCL), winter rye treatments (DikopshofWR), and organic crop rotations (Frankenhausen) as affected by management activities. Error bars represent the standard error of the mean; Different letters indicate significant differences at $P < 0.05$ (Tukey). For Dikopshof, compact letter displays are based on repeated within-plot measurements. As the historical design lacks independent field-scale replication, treatment differences should be interpreted cautiously.

However, potatoes at Frankenhausen and clover at Dikopshof still had the lowest emissions.

At Asendorf, area-based nitrous oxide emissions varied among treatments, with the lowest values observed under Phacelia and Mix4 and the highest under Fallow and Oat. Clover, Mix12, and Mustard formed intermediate groups. The Mix4 treatment was significantly lower than Clover, Oat, and Fallow, while Phacelia was significantly lower than Oat and Fallow ($P < 0.05$). A similar pattern was observed for yield-scaled nitrous oxide emissions. Phacelia and Mix4 showed the lowest values, followed by Clover, whereas Mix12, Mustard, Fallow, and Oat exhibited higher emissions. Oat and Fallow were significantly higher than Phacelia and Clover ($P < 0.05$), while Mix4, Mustard, and Mix12 did not differ significantly from the other treatments.

At Frankenhausen, neither area-scaled nor yield-scaled nitrous oxide emissions differed significantly among the management systems ($P > 0.05$). Area-scaled emissions ranged from 2.19 ± 0.11 under the compost-based system to 2.79 ± 0.26 kg N ha⁻¹ yr⁻¹ under the vegan cut-and-carry system, with the mixed farming system showing intermediate values. Similarly, yield-scaled emissions ranged from 302.17 ± 17.18 under the compost-based system to 396.54 ± 32.72 mg N₂O kg⁻¹ DM under the vegan cut-and-carry system, while the mixed farming system again showed intermediate values. In contrast, during the Dikopshof clover phase, area-scaled emissions differed significantly among nutrient replacement strategies ($P < 0.05$). The lowest emissions were observed under _PKCa and NPKCa. Slightly higher values were observed under NPK and the unfertilised control, but these did not differ significantly from the lowest-emission treatments. Emissions increased further under _PKCa+m and manure-only (m), while the highest emissions were recorded under NPKCa+m+s. Differences between _PKCa and NPKCa were not significant, and NPK_ did not differ significantly from NPKCa ($P > 0.05$). A similar pattern was observed for yield-scaled N₂O emissions. The lowest values occurred under NPKCa, followed by _PKCa and PKCa+m. Intermediate values were observed under NPK_ and

the unfertilised control, whereas the highest yield-scaled emissions were recorded under NPKCa+m+s and manure-only (m).

For the winter rye phase at Dikopshof, area-scaled N₂O emissions ranged from 0.31 ± 0.06 kg N ha⁻¹ yr⁻¹ under _PKCa to 9.24 ± 5.55 kg N ha⁻¹ yr⁻¹ under manure-only (m). The _PKCa treatment showed the lowest emissions and was significantly lower than PKCa+m ($P < 0.05$). Other treatments exhibited higher mean emissions, although substantial variability limited statistical separation. In general, treatments receiving nitrogen inputs showed elevated emissions, ranging from approximately two- to eleven-fold higher than the unfertilised control. Yield-scaled emissions followed a similar pattern, with the lowest values under _PKCa and significantly higher emissions under PKCa+m. Although the remaining treatments also showed higher mean yield-scaled emissions, high variability again limited statistical differentiation among treatments.

3.3.2. Carbon dioxide emissions

Across sites and crop phases, cumulative CO₂-C emissions (soil respiration) showed moderate variation but generally weak treatment separation (Fig. 8A). At Asendorf, emissions ranged from 8.96 to 10.30 Mg C ha⁻¹ yr⁻¹. Oat and the 12-species mixture treatments showed higher emissions than Fallow and Clover ($P < 0.05$), while Mix4, Mustard, and Phacelia formed intermediate groups ($P > 0.05$). At Frankenhausen, cumulative CO₂-C emissions were tightly clustered (9.05 – 10.56 Mg C ha⁻¹ yr⁻¹) and did not differ significantly among the organic systems ($P > 0.05$). At Dikopshof, CO₂-C emissions during the clover phase ranged from 7.93 to 10.62 Mg C ha⁻¹ yr⁻¹. The highest emissions were observed under PKCa+m, whereas NPKCa and NPK showed the lowest values; the remaining treatments fell between the highest and lowest treatments, with significant differences between them ($P < 0.05$). During the winter rye phase, emissions ranged from 12.58 to 24.38 Mg C ha⁻¹ yr⁻¹. NPK_ showed higher emissions than several treatments, including _PKCa, _PKCa+m, NPKCa, and the

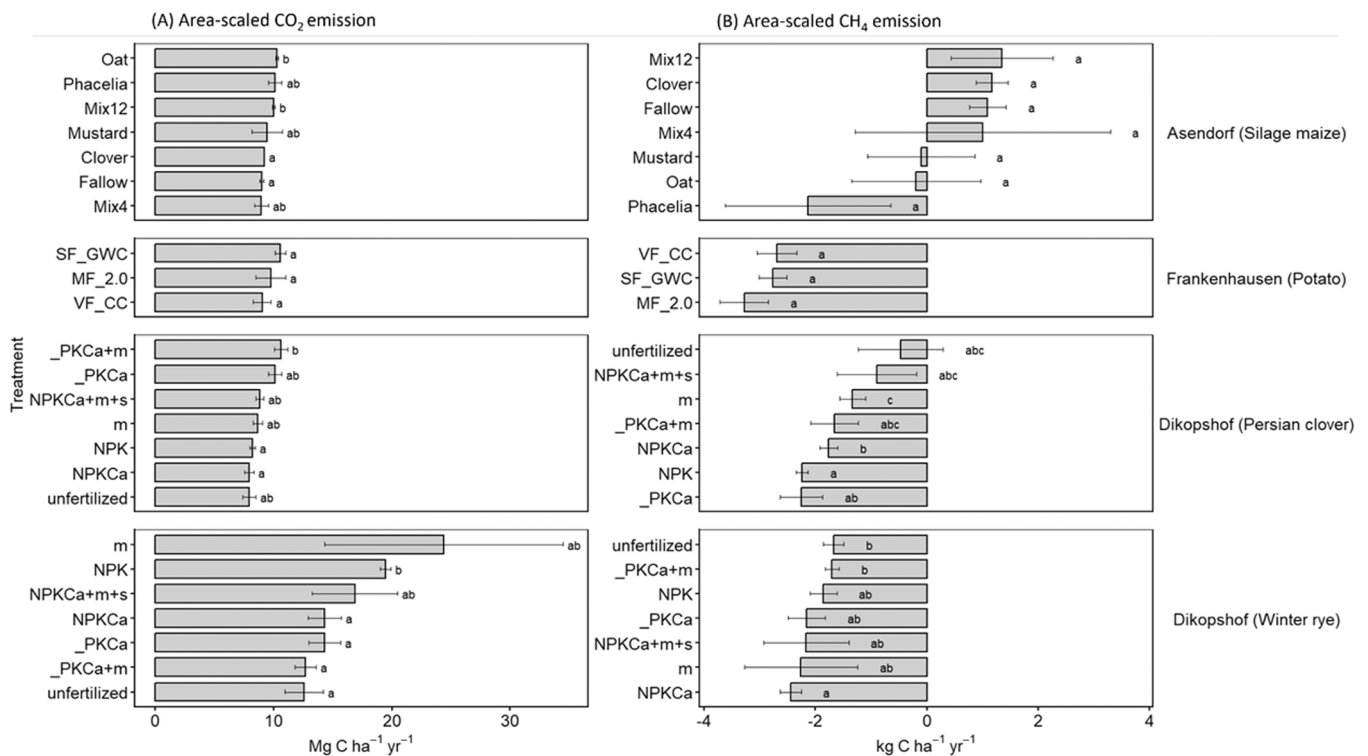


Fig. 8. Cumulative CO₂-C (A) and CH₄-C (B) fluxes from catch crop treatments (Asendorf), nutrient replacement treatments under Persian clover and winter rye treatments and organic crop rotations (Frankenhausen) as affected by management activities. Error bars represent the standard error of the mean; Different letters indicate significant differences at $P < 0.05$ (Tukey). For Dikopshof, compact letter displays are based on repeated within-plot measurements. As the historical design lacks independent field-scale replication, treatment differences should be interpreted cautiously.

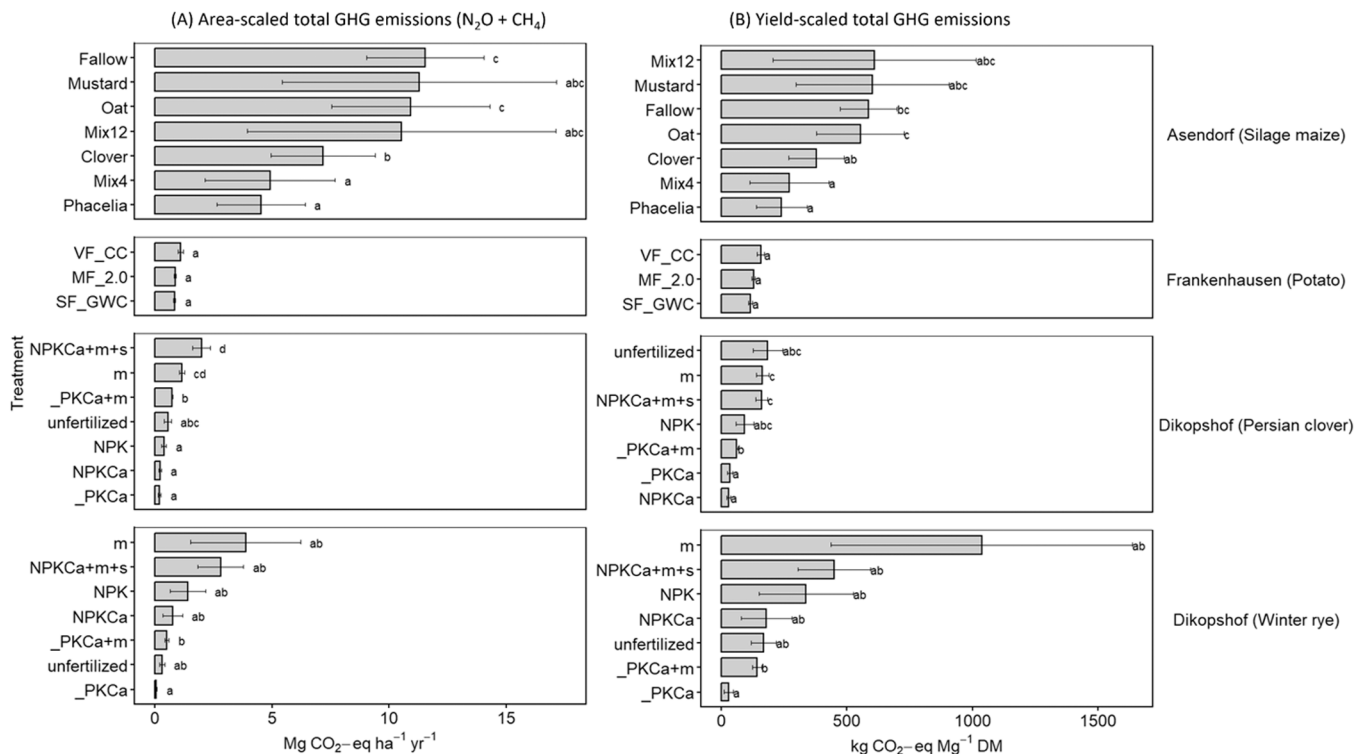


Fig. 9. Area-scaled (A) total greenhouse gas (GHG) emissions (N₂O + CH₄; Mg CO₂ equivalence (e) ha⁻¹ yr⁻¹) and yield-scaled (B) GHG emissions (B, kg CO₂e kg⁻¹ dry matter yield (DM)) from catch crop treatments (Asendorf), nutrient replacement treatments under Persian clover, winter rye treatments and organic crop rotations (Frankenhausen) as affected by management activities. Error bars represent the standard error of the mean; Different letters indicate significant differences at $P < 0.05$ (Tukey). For Dikopshof, compact letter displays are based on repeated within-plot measurements. As the historical design lacks independent field-scale replication, treatment differences should be interpreted cautiously.

unfertilised control ($P < 0.05$), while the remaining treatments formed intermediate groups.

3.3.3. Methane emissions

Annual methane balances were small across all sites and crop phases, with soils generally acting as weak net methane sinks or remaining close to methane neutral (Fig. 8B). At Asendorf, methane balances ranged from -2.14 to $+1.34$ kg $\text{CH}_4\text{-C ha}^{-1} \text{ yr}^{-1}$, with no significant differences among cover-crop treatments ($P > 0.05$). Although differences were not statistically significant, the Mustard, Oat and Phacelia treatments acted as net methane sink, whereas the remaining treatments were weak sources. At Frankenhausen, all systems functioned as net methane sinks (-3.28 to -2.69 kg $\text{CH}_4\text{-C ha}^{-1} \text{ yr}^{-1}$), again with no significant treatment effects observed ($P > 0.05$). At Dikopshof, soils also acted predominantly as methane sinks during both crop phases. During the clover phase, methane balances ranged from -2.25 to -0.47 kg $\text{CH}_4\text{-C ha}^{-1} \text{ yr}^{-1}$, with significantly lower methane uptake under under mineral fertilisation without liming (NPK) compared with manure-only treatment ($P < 0.05$), while the remaining treatments showed intermediate values. During the winter rye phase, methane balances ranged from -2.45 to -1.68 kg $\text{CH}_4\text{-C ha}^{-1} \text{ yr}^{-1}$. Complete mineral fertilisation with liming (NPKCa) showed the strongest methane uptake, while mineral fertilisation without nitrogen but with liming plus manure (PKCa+m) and the unfertilised control exhibited lower uptake ($P < 0.05$). The remaining treatments formed intermediate groups.

3.3.4. Total greenhouse gas emissions

Across sites and crop phases, total annual greenhouse gas balances based on N_2O and CH_4 emissions, expressed as CO_2 -equivalents, varied substantially (Fig. 9 A-B). At Asendorf, total greenhouse gas balances ranged from 4.54 to 11.54 t $\text{CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$. The lowest area-scaled emissions were observed under Phacelia and Mix4 treatments, while the highest were observed under Oat and Fallow. Clover showed intermediate emissions, whereas Mix12 and Mustard overlapped with both the lower- and higher-emitting treatments. Oat and Fallow were significantly higher than Phacelia and Mix4 ($P < 0.05$). Yield-scaled emission intensities ranged from 240 to 610 kg $\text{CO}_2\text{-eq t}^{-1} \text{ DM}$. The lowest emissions were observed under Phacelia and Mix4, whereas the highest occurred under Oat and Fallow treatments. Clover exhibited intermediate emissions, while Mix12 and Mustard overlapped statistically with both the lower- and higher-emitting treatments. Oat and Fallow showed significantly higher emissions than Phacelia and Mix4 ($P < 0.05$).

At Frankenhausen, cumulative trace gas balances ranged from 837.7 to 1098.8 kg $\text{CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$. The lowest area-scaled emissions were observed under the compost-based system and the mixed farming system, while the vegan cut-and-carry system showed numerically higher emissions; however, differences among the organic farming systems were not significant ($P > 0.05$). Yield-scaled emission intensities ranged from 115.8 to 156.2 kg $\text{CO}_2\text{-eq t}^{-1} \text{ DM}$. The compost-based system exhibited the lowest emission intensities, while the vegan cut-and-carry system showed the highest values, with the mixed farming system occupying an intermediate position. Nevertheless, no significant differences were detected among treatments ($P > 0.05$).

At Dikopshof during the clover phase, area-scaled trace gas balances ranged from 204.9 to 1985.2 kg $\text{CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$ and differed significantly among nutrient replacement strategies ($P < 0.05$). The lowest emissions were observed under mineral fertilisation without nitrogen but with liming (PKCa), complete mineral fertilisation with liming (NPKCa), and mineral fertilisation without liming (NPK). Higher emissions occurred under mineral fertilisation without nitrogen but with liming plus manure (PKCa+m), while the manure-only treatment and combined mineral-organic fertilisation with liming and elevated nitrogen input (NPKCa+m+s) showed the highest emissions, whereas the unfertilised treatment formed an intermediate group. Yield-scaled emission intensities ranged from 28.8 to 184.9 kg $\text{CO}_2\text{-eq t}^{-1} \text{ DM}$. The

lowest values were observed under NPKCa and PKCa, followed by PKCa+m, with moderate emissions. Higher intensities were observed under NPKCa+m+s and manure-only treatment, while NPK and the unfertilised control formed intermediate groups.

Area-scaled trace gas balances ranged from 54.7 to 3879.0 kg $\text{CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$ during the winter rye phase. The lowest emissions occurred under PKCa, which was significantly lower than PKCa+m ($P < 0.05$). The unfertilised control, NPKCa, NPK, NPKCa+m+s, and manure-only treatment showed intermediate values and did not differ significantly from either treatment. Numerically, emissions increased from the mineral PKCa treatment towards systems receiving organic or combined nutrient inputs, with the highest values observed under manure-only and NPKCa+m+s. Yield-scaled emission intensities ranged from 28.1 to 1036.6 kg $\text{CO}_2\text{-eq t}^{-1} \text{ DM}$. The lowest values were observed under PKCa, while PKCa+m showed significantly higher intensities ($P < 0.05$). The remaining treatments, including the unfertilised control, NPKCa, NPK, NPKCa+m+s, and manure-only treatment, formed an intermediate group and did not differ significantly from one another, although numerically higher intensities were associated with the manure-only and combined mineral-organic fertilisation treatments.

4. Discussion

4.1. Site-specific crop productivity

Crop productivity across the three experimental sites reflected interactions among crop functional traits, nutrient supply, and location-dependent soil conditions. At Asendorf, silage maize yields differed only slightly among cover-crop and fallow treatments, with values ranging from 18.4 to 19.7 Mg $\text{DM ha}^{-1} \text{ yr}^{-1}$. These differences were small and mostly not statistically significant, although Oat showed slightly higher yields than Phacelia. The narrow yield range indicates that maize productivity under the prevailing management was largely insensitive to short-term variation in the identity of the preceding cover crop. This agrees with previous studies showing that nitrogen contained in cover crop residues is often temporarily immobilised during early maize development and therefore contributes more to longer-term soil organic matter formation than to immediate crop nitrogen supply (Constantin et al., 2012; Gentsch et al., 2020; Poeplau and Don, 2015). A similarly small response range was observed at Frankenhausen, where potato yields varied only modestly across the three organic crop rotations. Although the compost-based rotation produced numerically higher yields than the mixed farming system and the vegan cut-and-carry system, these differences were not statistically significant. Such yield stability is consistent with the buffering capacity commonly observed in organic systems, where gradual nutrient release from organic amendments and improved soil structure contribute to relatively stable crop productivity (Gattinger et al., 2012; Hartmann et al., 2015; Usman et al., 2012). Notably, both the experiment at Asendorf and the experiment at Frankenhausen are rather young field trials; therefore, stronger treatment effects on crop yields may emerge over longer experimental durations.

In contrast, the long-term experiment at the Dikopshof site showed stronger, treatment-specific yield responses, reflecting pronounced differences in nutrient availability among fertilisation strategies resulting from more than a century of continuous management since 1904. During the Persian clover phase, biomass yields varied substantially among treatments, ranging from about 3.1 Mg DM ha^{-1} in the unfertilised control to more than 12 Mg DM ha^{-1} under combined mineral-organic fertilisation with liming and under the manure treatment supplemented with phosphorus, potassium and liming but without mineral nitrogen. Balanced mineral fertilisation with liming and the manure-only treatment resulted in intermediate productivity. Lower yields were observed when key nutrients were omitted, particularly under the phosphorus-potassium treatment with liming, complete mineral fertilisation without liming, and the unfertilised control. These results indicate that

clover productivity was strongly influenced by overall nutrient balance rather than nitrogen supply alone. Although legumes can meet a substantial portion of their nitrogen demand through biological nitrogen fixation, the efficiency of this symbiosis is tightly regulated by the availability of phosphorus, potassium, and other macro- and micro-nutrients, which control nodule formation, nitrogenase activity, and plant-microbe metabolic interactions (Cabeza et al., 2024; Ma et al., 2025; Solangi et al., 2024; Zhang et al., 2024). The higher yields observed in treatments receiving both organic amendments and balanced nutrient inputs, therefore, likely reflect improved nutrient availability and enhanced soil biological activity.

Winter rye showed a contrasting response pattern, characterised by a stronger dependence on mineral nitrogen availability. Grain yields ranged from approximately 1.8 Mg DM ha⁻¹ in the unfertilised control and the phosphorus–potassium treatment with liming (without mineral nitrogen) to more than 6 Mg DM ha⁻¹ under combined mineral–organic fertilisation with liming. Intermediate yields were obtained under complete mineral fertilisation with and without liming, as well as under manure-only and manure-amended phosphorus-potassium treatments with liming. These results highlight the importance of readily available nitrogen for cereal productivity, particularly during early growth stages when rapid canopy development and tillering strongly influence final yield formation (Hirel et al., 2011; Jensen et al., 2010). Although complete mineral fertilisation with liming produced numerically higher rye yields than complete mineral fertilisation without liming, the difference was not statistically significant. Liming may improve root development, soil structure, nutrient retention, and physiological regulation (Coelho et al., 2022; Quirk and Schofield, 1955; Wuddivira and Camps-Roach, 2007), but under the conditions of this study these effects did not translate into a consistent yield advantage. Overall, nitrogen availability remained the dominant control on cereal productivity, while manure-derived inputs appeared most beneficial when combined with mineral nitrogen. Placed in a broader agronomic context, yields across sites were comparable to regional production levels reported for Germany (Duden et al., 2024), indicating that the best-performing systems in this experiment achieved productivity levels within realistic commercial production ranges.

4.2. Drivers of greenhouse gas fluxes

Across all sites, gas fluxes were governed by short-lived responses to weather and management events, with treatment effects outside peak periods generally limited. Site-averaged fluxes for carbon dioxide, nitrous oxide, and methane fell within ranges reported for temperate croplands (Gao et al., 2022; Oertel et al., 2016; Winkhart et al., 2022; Zentgraf et al., 2025), confirming that the observed dynamics are typical of managed arable soils. However, nitrous oxide emissions were characterised by highly episodic peaks. While short-term fluxes exceeding 2000 µg N m⁻² h⁻¹ are frequently reported for maize-based systems following fertiliser application under favourable moisture and temperature conditions (Winkhart et al., 2022), substantially higher peaks have also been documented for cropping systems. For example, (Jia et al., 2012) reported extreme fluxes up to 37,491 µg N m⁻² h⁻¹ across different crop rotations, with several additional peaks exceeding 10,000 µg N m⁻² h⁻¹. The annual emissions observed at Asendorf (10.8–26.8 kg N ha⁻¹ yr⁻¹) are comparable to the 5.6–19.0 kg N ha⁻¹ yr⁻¹ reported for digestate-fertilised silage maize systems in southern Germany (Winkhart et al., 2022), 12–17 kg N ha⁻¹ yr⁻¹ in northern Italy (Maris et al., 2021), attributable to the combined effects of high nitrogen availability, intensive soil disturbance, and favourable hydrothermal conditions. Similarly, (Kemmann et al., 2023) reported “extremely high” emission peaks from maize grown on fine-textured, poorly drained Stagnosols in western Germany, identifying subsoil compaction and temporary waterlogging as key amplifying factors.

A comparison across sites indicates that these extreme emissions at Asendorf likely resulted from a unique convergence of drivers that were

less pronounced at Frankenhausen and Dikopshof. First, soil texture and hydrological conditions differed substantially among sites. The silty, loess-derived soils at Asendorf are prone to temporary surface sealing and high-water retention, promoting denitrification following rainfall (Velthof et al., 2020; Kemmann et al., 2023), whereas the deeper loess and better-structured soils at Dikopshof and the organically managed soils at Frankenhausen likely maintained higher gas diffusivity, limiting the formation of anaerobic microsites. Second, the timing of fertilisation relative to precipitation appears critical. At Asendorf, mineral nitrogen application coincided with warm and moist conditions, favouring rapid nitrification–denitrification turnover, whereas at the other sites, fertilisation and rainfall events were less synchronised, resulting in smaller emission peaks. Third, differences in residue quality and carbon-to-nitrogen ratio may have further modulated nitrous oxide responses. The incorporation of labile cover crop residues at Asendorf likely enhanced microbial respiration and oxygen consumption, thereby stimulating denitrification, while residue inputs at Frankenhausen and Dikopshof were either more stabilised (e.g. compost-based systems) or temporally decoupled from peak mineral nitrogen availability. Moreover, the placement of ammonium nitrate fertiliser beneath maize seeds at sowing likely led to high local mineral nitrogen concentrations that, when combined with wet soil conditions after planting, created favourable conditions for rapid nitrification–denitrification turnover. Together, these factors suggest that extreme nitrous oxide emissions arise from the interaction of multiple site-specific controls rather than from management alone. The results therefore support the concept of “hot moments” in nitrous oxide production, where synchronisation of substrate availability, soil moisture, and temperature can lead to disproportionately high emissions (Ábalos et al., 2016; Winkhart et al., 2022).

The episodic nature of nitrous oxide fluxes at Frankenhausen, with peaks reaching up to 400 µg N m⁻² h⁻¹ in the vegan cut-and-carry system, aligns with the pattern observed in other Central European organic systems, where the incorporation of legume-rich green manures and organic amendments can create short-lived but significant emission pulses (Chmelíková et al., 2021; Scialabba, Müller-Lindenlauf, 2010). The higher peaks in the vegan cut-and-carry system likely reflect the rapid mineralisation of its plant-based inputs (tofu whey and fresh clover mulch), which, as noted by Saha et al. (2021), can create transient hypoxia when labile carbon and nitrogen inputs coincide. Also, the pronounced nitrous oxide responses observed in manure-amended treatments (m, NPKCa+m+s) during the clover and winter rye phases at Dikopshof are consistent with the broader Central European evidence that organic amendments, particularly when combined with mineral nitrogen, elevate the risk of denitrification losses, especially on fine-textured soils prone to temporary waterlogging (Winkhart et al., 2022; Velthof et al., 2020). The substantial peak during the February 2025 freeze–thaw event in manure-treated plots further supports the recognition that such climatic events are critical drivers of annual nitrous oxide budgets in temperate regions (Ábalos et al., 2016).

Accordingly, annual nitrous oxide emissions were dominated by episodic peaks rather than sustained background fluxes, consistent with studies showing that short-term events such as fertilisation, wetting, tillage, and freeze–thaw cycles contribute disproportionately to nitrous oxide budgets (Groffman et al., 2009; Ruser et al., 2017). At Asendorf, near-zero nitrous oxide fluxes punctuated by pronounced pulses spanning three weeks, following fertilisation, constituted 64–89% of annual emissions, driven by temperature-moisture interactions (Skinner, et al., 2014). At Frankenhausen and Dikopshof, repeated nitrous oxide peaks followed discrete management events, and wet conditions, including freeze–thaw periods, amplified these responses, in line with findings that soil moisture regimes modulate denitrification and nitrification pathways (Butterbach-Bahl et al., 2013; Petersen et al., 2008). Significant treatment effects on nitrous oxide were observed only during the clover phase at Dikopshof, where strategies combining mineral and organic inputs increased peak emissions relative to low-nitrogen or

nitrogen-omission systems. This confirms that nitrogen availability, rather than average seasonal conditions, is a key prerequisite for large nitrous oxide losses induced by management (van Groenigen et al., 2004). Importantly, elevated carbon dioxide fluxes associated with enhanced biological activity did not necessarily coincide with high nitrous oxide emissions, underscoring that nitrous oxide production requires not just biological activity but also excess mineral nitrogen coupled with transient anaerobic microsites (Firestone et al., 1989).

Although methane fluxes were small relative to nitrous oxide and carbon dioxide, clear differences among sites and treatments provide insight into the underlying controls of methane exchange. Across all sites, soils predominantly acted as weak methane sinks, consistent with well-aerated temperate cropland soils where methanotrophic oxidation typically exceeds methanogenesis (Le Mer and Roger, 2001). The consistently negative methane balances at Frankenhausen and Dikopshof further reflect favourable soil aeration and structure, which promote gas diffusivity and sustain methanotrophic activity. In contrast, near-neutral or slightly positive methane balances observed at Asendorf in some cover-crop treatments indicate temporary constraints on methane oxidation rather than sustained methanogenesis. These conditions are likely linked to short-term increases in soil moisture following precipitation or enhanced microbial activity from residue inputs, both of which can reduce oxygen availability and limit methane diffusion into the soil (Hu et al., 2023; Smith et al., 2018). This interpretation aligns with findings by Bayer et al. (2012), who showed that systems with high carbon-to-nitrogen ratio in residues tend to maintain methane uptake, whereas legume-based systems with more labile, nitrogen-rich residues can promote transient methane emissions through increased oxygen consumption and the formation of anaerobic microsites (Ebrahimi and Or, 2017). Additionally, ammonium released during rapid residue decomposition may competitively inhibit methane monooxygenase, further suppressing methanotrophic activity (Bodelier and Laanbroek, 2004). As a result, the balance may temporarily shift from net methane uptake to weak emissions. These effects are typically short-lived and highlight the sensitivity of methane fluxes to transient changes in soil moisture, oxygen availability, and substrate supply (Gentsch et al., 2024; Nazaries et al., 2013; Tate, 2015).

Differences among treatments at Dikopshof, particularly the reduced methane uptake under mineral fertilisation compared with manure-based systems, further suggest that nutrient management can influence methanotrophic activity. Mineral nitrogen inputs have been reported to inhibit methane oxidation, likely due to competitive interactions between ammonium and methane for the methane monooxygenase enzyme in methanotrophs (Lehmann et al., 2020a). In contrast, organic amendments may enhance soil structure and microbial habitat conditions, thereby supporting methane uptake. These results indicate that methane fluxes, although small, respond to site conditions and management practices. Future studies combining high-frequency measurements with analyses of soil physical properties and microbial functional groups (e.g. methanotroph activity) would be valuable to better disentangle the mechanisms controlling methane exchange in agroecosystems.

Cumulative carbon dioxide emissions, ranging from 8 to 26 Mg C ha⁻¹ yr⁻¹ across all treatments and sites, were within the broad range reported for European arable systems (Janssens et al., 2003; Raich and Schlesinger, 1992) and reflected seasonal temperature trends, soil moisture, and crop development more than the fertilisation strategy per se. Across sites, carbon dioxide fluxes increased with crop growth and disturbance events (e.g., tillage, residue incorporation), consistent with respiration responses documented in managed soils (Davidson and Janssens, 2006). Treatment effects in cumulative carbon dioxide were generally weak, except at Dikopshof, where integrated organic C inputs and soil disturbance coincided with higher respiration pulses. Across all experiments, soils consistently acted as weak methane sinks, a pattern typical for well-aerated temperate croplands dominated by methanotrophic oxidation (Dutaur and Verchot, 2007; Smith and Conen, 2004).

Methane fluxes fluctuated around zero with only minor treatment differentiation, indicating that treatment impacts on methane exchange were small relative to site and soil physicochemical drivers. It must be noted that, apart from the organic rotations which demonstrated consistent temporal CH₄ uptake, the other sites showed losses, with net emissions in some cover crop treatments at Asendorf.

4.3. Total greenhouse gas emissions and system-level climate efficiency

System-level climate efficiency reflected the combined influence of site conditions, crop phase, nutrient strategy, and productivity, rather than any single management factor. Across all systems, total trace gas balances were dominated by episodic nitrous oxide peaks, while methane contributed only marginally to overall budgets, consistent with previous assessments of temperate arable land (Aronson and Allison, 2012; Dutaur and Verchot, 2007). This confirms that mitigation potential in cropland systems is governed primarily by controls on nitrous oxide formation, rather than by changes in methane exchange.

4.3.1. Cover crop effects

At Asendorf, differences in total trace gas balances (derived from nitrous oxide and methane emissions) were driven primarily by treatment effects on nitrous oxide, as methane fluxes were negligible and carbon dioxide emissions were considered separately as soil respiration. The observed nitrous oxide emissions were within the upper range reported for southern Germany by Winkhart et al. (2022) (up to 19.0 kg ha⁻¹ yr⁻¹) and comparable to simulated maxima for Austrian maize systems (12.5 kg ha⁻¹ yr⁻¹; Foldal et al., 2024). Lower mean emissions under Phacelia and Mix4 suggest improved nitrogen retention and a closer synchrony between nitrogen release and maize nitrogen uptake. This interpretation aligns with studies showing that Phacelia-based cover crops enhance nitrate scavenging and reduce nitrogen losses from cropping systems (Kliszcz et al., 2023). Moreover, cover crop mixtures with complementary rooting traits can improve nitrogen capture and delay nitrogen release through enhanced microbial immobilisation and better synchronisation with crop demand (Blesh, 2018). Phacelia has been reported to exhibit strong nitrate scavenging capacity and, in some cases, lower nitrous oxide emission peaks compared with other cover crop species (Kliszcz et al., 2023; Żarczyński et al., 2025). This may reflect not only rapid nitrogen uptake but also root traits that improve soil structure and aeration, thereby reducing the formation of anaerobic microsites during periods with high denitrification risk.

In contrast, the comparatively higher emissions observed under Mix12 and Oat indicate that greater catch-crop diversity or specific functional groups do not automatically confer nitrous oxide mitigation benefits. This finding is consistent with the global synthesis by Abdalla et al. (2019), which reported no consistent reduction in direct nitrous oxide emissions from cover crops and highlighted the risk of increased emissions from legume-based systems due to their low carbon-to-nitrogen ratios. Similarly, modelling studies of European cropping systems emphasise that cover crop selection is critical, with shifts from leguminous to grass-based systems reducing nitrous oxide losses under conditions of positive net trace gas fluxes (Quemada et al., 2020). At Asendorf, the Oat treatment, characterised by relatively high biomass and a moderate carbon-to-nitrogen ratio, may have stimulated microbial activity and nitrogen mineralisation following incorporation, thereby increasing the pool of mineral nitrogen available for nitrous oxide production after maize fertilisation. Likewise, despite its higher species diversity, the 12-species mixture likely contained sufficient legume biomass to increase residue-derived nitrogen inputs. Saha et al. (2021) demonstrated that nitrous oxide emissions can increase sharply when legume-derived biomass exceeds thresholds. These findings are consistent with broader evidence that plant functional traits and belowground allocation patterns regulate soil nitrogen transformations and nitrous oxide production (Nyameasem et al., 2021a), and that

increased plant diversity does not inherently translate into lower emissions. For instance, multispecies grassland systems have shown no reduction in nitrous emission peaks from urine and dung patches compared with simpler swards (Nyameasem et al., 2021b). Thus, the effectiveness of cover crops for nitrous oxide mitigation is highly context-dependent and governed by residue quality, timing of nitrogen release, and interactions with fertiliser inputs and environmental conditions.

4.3.2. Soil fertility management effects

A comparable buffering of treatment effects was observed at Frankenhof, where potato yield and cumulative area-scaled trace gas balances were tightly grouped across organic fertility strategies. Significant differences in climate efficiency did not emerge when emissions were normalised to productivity, although a trend of the compost-based system < the mixed farming system < the vegan cut-and-carry system was observed, attributable to the slightly higher yields under the compost-based system. Previous findings show that, under long-term organic management, yield variability often governs greenhouse gas emission intensity more strongly than absolute emissions per unit area (Gattinger et al., 2012; van Groenigen et al., 2010). In contrast, the Dikopshof experiment exhibited pronounced crop-phase specificity in system-level responses. During the clover phase, differences in productivity strongly modulated yield-scaled emission intensities, with integrated nutrient strategies offsetting higher emissions associated with increased biomass productivity. During the winter rye phase, by contrast, system-level greenhouse gas balances were characterised by an elevated risk of emissions associated with high nitrogen availability, soil disturbance, and moist autumn and winter conditions. Under these circumstances, yield-scaled metrics provided clearer differentiation among nutrient strategies than area-based balances, reinforcing that climate efficiency cannot be inferred from absolute emissions alone (Abalos et al., 2020).

Across crop phases, lime-supported mineral and integrated mineral-organic fertilisation tended to improve climate efficiency where nitrogen supply was aligned with crop demand. These effects are likely linked to improved soil structure, aeration, and nutrient uptake, reducing the coincidence of surplus mineral nitrogen and anaerobic microsites that promote nitrous oxide formation (Rowley et al., 2018; Six et al., 2004; Vekic et al., 2023). However, such benefits were neither universal nor independent of crop phase, underscoring that the effects of fertilisation and liming must be interpreted within their specific biogeochemical and temporal context. These findings demonstrate that system-level climate efficiency in temperate cropping systems is inherently site- and phase-dependent. Where significant differences occurred, they were most consistently reflected in yield-scaled emission intensities rather than in area-based balances, indicating differences in productivity rather than in absolute emissions. Effective mitigation, therefore, requires phase-specific nutrient management that limits nitrogen surpluses during high-risk periods while sustaining yields, rather than uniform reductions in input intensity across systems.

This study provides insights into greenhouse gas dynamics under long-term nutrient management; however, several limitations should be acknowledged. First, long-term fertilisation experiments inherently reflect site-specific soil, climate, and management histories, which may limit the generalisability of individual treatment effects. Although the inclusion of multiple sites partially mitigates this constraint, the observed responses should be interpreted within their pedoclimatic context. In addition, the Dikopshof experiment follows a historical design without true field-scale replication, which may introduce pseudoreplication when within-plot measurements are used as statistical units. Consequently, treatment effects at this site should be interpreted with caution, as variability between treatments cannot be fully separated from potential spatial heterogeneity. Rather than providing strict inferential comparisons, the Dikopshof data are best understood as indicative of long-term system responses and legacy effects under

contrasting fertilisation regimes.

Second, while long-term applications of manure and mineral fertilisers are known to influence organic carbon pools and microbial processes, the present study does not directly resolve the underlying mechanisms. Long-term fertilisation can alter both the quantity and quality of carbon, affecting the balance between labile and stabilised carbon fractions and thereby regulating microbial activity and substrate availability for biogeochemical processes (Gattinger et al., 2012; Lehmann et al., 2020b). Organic amendments typically enhance microbial biomass and carbon inputs, which can stimulate decomposition and short-term carbon dioxide and nitrous oxide fluxes, whereas mineral fertilisation may accelerate organic carbon turnover through increased plant productivity and rhizodeposition (Tang et al., 2024).

These changes in soil carbon dynamics are closely linked to shifts in microbial community composition and functional activity, including nitrifiers, denitrifiers, and heterotrophic decomposers, which ultimately control trace gas fluxes. However, as carbon fractions and microbial functional groups were not explicitly measured in this study, gas fluxes should be interpreted as integrated system responses arising from the interaction of carbon inputs, nutrient availability, and microbial regulation. This highlights that the net effect of long-term fertilisation on greenhouse gas emissions cannot be attributed to a single driver but emerges from coupled soil–plant–microbial processes.

Finally, the absence of detailed mechanistic measurements limits the ability to explicitly disentangle these pathways. Future research combining long-term experiments with process-based measurements of organic carbon fractions, microbial functional groups, and isotopic tracing approaches would further improve mechanistic understanding. Despite these limitations, the present study provides robust empirical evidence on the integrated, long-term effects of nutrient management on greenhouse gas emissions and climate efficiency in cropping systems.

5. Conclusion

Greenhouse gas dynamics in the temperate arable systems under study were primarily governed by interactions among site conditions, crop phase, and nutrient management. Across sites, nitrous oxide dominated treatment responses and overall greenhouse gas balances, with pronounced emission peaks occurring after fertilisation, residue incorporation, soil disturbance, and freeze–thaw events. These findings indicate that emissions were controlled less by average management intensity than by the timing of management operations relative to transient environmental conditions, particularly soil moisture and temperature.

The high nitrous oxide peaks observed at Asendorf place this system within a broader Central European “high-risk” context, characterised by elevated mineral nitrogen availability, incorporation of cover crop residues, intensive tillage, and episodic climatic triggers. Within this framework, Phacelia and the functionally diverse mixtures (e.g., Mix4) tended to reduce emissions relative to the fallow and oat systems, suggesting that cover crop identity and residue quality influence nitrogen retention and subsequent emission risks. However, these effects depended strongly on soil conditions, nutrient status, and moisture regimes, highlighting the need for context-specific, trait-based cover crop strategies.

In contrast, carbon dioxide fluxes were mainly driven by seasonal soil respiration and disturbance effects, while methane exchange remained small, with soils generally acting as weak sinks. Consequently, overall greenhouse gas balances were largely determined by nitrous oxide dynamics. Responses to nutrient management also differed among systems: cover crop composition was particularly important in the maize system at Asendorf, whereas organic fertility strategies had limited effects in the potato system at Frankenhof. At Dikopshof, however, long-term nutrient replacement treatments strongly influenced emissions, especially under manure-only and combined mineral-organic fertilisation.

Overall, the results demonstrate that improving climate efficiency in temperate cropping systems requires phase-specific nitrogen management that limits periods of surplus mineral nitrogen. At Asendorf, lower emissions under Phacelia and Mix4, which reduced area- and yield-scaled greenhouse gas emissions by approximately half relative to Fallow and Oat-based systems, highlight the potential of nitrate-scavenging and functionally complementary cover crops. In contrast, the elevated emissions observed under manure-based and combined fertilisation at Dikopshof emphasise the risks associated with excessive nitrogen availability during wet and freeze-thaw conditions. The comparatively stable yields and tightly grouped greenhouse gas balances in the compost-based organic system at Frankenhausen further suggest that management supporting soil structure, aeration, and balanced nutrient cycling can help moderate emission peaks while sustaining productivity. Future research should further integrate long-term experimental evidence with process-based modelling to better capture event-driven emission dynamics and support the development of robust mitigation strategies under increasing climatic variability.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2026.110519](https://doi.org/10.1016/j.agee.2026.110519).

Data availability

Data will be made available on request.

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