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Comparison of organic versus conventional farming: results from long-term lysimeter studies

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Introduction: Organic farming (OF) has established itself as an alternative to conventional farming. Currently, only a few results are available from long-term studies examining the effects of OF on the environment and agriculture.
Methods: The effects of organic soil cultivation were investigated in a 32-year long-term experiment (from 1991 to 2023) using non-weighable gravity lysimeters, taking into account the known limitations of this method, and compared with agriculture based on best management practices (BMP) cultivation principles with regard to nitrogen leaching via seepage and other parameters, such as yield, nitrogen uptake, and nitrogen use efficiency.
Results: Compared with BMP, OF showed an average annual increase of 25 mm in seepage volume over the long term. Nitrogen concentrations in seepage water did not differ significantly between the two farming systems. The annual N load (median) was significantly higher for OF at 26.1 kg ha^{-1} than for BMP (20.5 kg ha^{-1}). In contrast, the OF lysimeters showed a 35% reduction in long-term dry matter yield.
Discussion: The organic management practiced here must be optimized to avoid long-term increases in N emissions. To achieve this, soil tillage intensity must be reduced, fallow periods during the vegetation-free season avoided, and the plowing of legumes in the fall obviated, as this can be associated with high N mineralization losses. The main challenge in increasing the share of OF in agricultural management systems is to enhance OF productivity by increasing yields and improving yield stability.

KEYWORDS
conventional farming, land use, long-term lysimeter study, nitrogen, organic farming, seepage

1 Introduction

Establishing productive yet sustainable land management that improves soil productivity while minimizing harmful impacts on climate, soil, water, air, biodiversity, and human health remains a current challenge for society. As an alternative to conventional farming, some areas are managed according to organic farming principles. In Europe, the share of organically managed land is currently 10.5%, and in Germany, 9.8% (EUROSTAT, 2025). Organic farming (OF) has been regulated in the European Union since 1990 by regulation (EU, 2018a), which sets minimum production standards, including the prohibition of mineral fertilizers and synthetic chemical pesticides. In Germany, there are additional guidelines of organic farming associations to be complied with (BMEL, 2023).

OF was evaluated as less efficient and less productive than conventional farming, due to lower yields and greater yield variability (Lakner and Breustedt, 2017; Smith et al., 2019). Overall, an organic yield gap of 35% was noted, meaning that more land is required to produce the same quantity of crops. A 35% yield gap means that 50% more arable land is required (Kirchmann, 2019). In Germany, the yield difference between organic and conventional farming was approximately 40% on average for all crops (Lin and Hülsbergen, 2017).

Despite lower yields than conventional farming, OF was found to be more efficient when environmental variables are taken into account (Lakner and Breustedt, 2017). To date, OF is the only well-defined, law-regulated, sustainable system in agriculture that produces foods clearly labeled for consumers (DWA, 2025). OF will become more important in the context of the European Commission's (EC, 2021) European Soil Strategy for 2030 and the upcoming Soil Monitoring Law, both of which promote more sustainable management to improve soil health. As shown previously in a meta-analysis by Lori et al. (2017), OF globally enhances soil microbial abundance and activity, thereby supporting various soil-based ecosystem services, such as nutrient cycling, carbon sequestration, and erosion control. Whereas the positive effects of OF systems on biodiversity, soil fertility, long-term soil organic carbon (SOC) sequestration, and water quality have been reported in several studies (Lori et al., 2017; Sanders and Hess, 2019; Sanders et al., 2025; DWA, 2025), the impact of OF on nitrate (NO_3^-) leaching is discussed controversially in the literature. NO_3^- dynamics in agricultural soils can be affected by many complex factors, including climate, soil properties, crop rotation, the proportion of legumes, the timing and intensity of soil tillage, and the presence of livestock (Knudsen et al., 2006; Biernat et al., 2020; DWA, 2025). On the one hand, numerous studies reported lower NO_3^- leaching of OF systems compared to conventional farming due to lower nitrogen (N) inputs and lower N balances as well as the integration of catch crops in the crop rotations resulting in lower N losses (Stopes et al., 2002; Benoit et al., 2016; Sanders and Hess, 2019; Hansen et al., 2020; DWA, 2025). It was previously presented in an analysis of 26 predominantly European studies that organic farms had 30% (mean) and 45% (median) lower N area balances than conventional farms (Chmelíková and Hülsbergen, 2019). A meta-analysis by the "Thünen Institute" of 71 studies on NO_3^- leaching showed substantial variation in results. On average, NO_3^- leaching was reduced by 28% (median) under organic farming compared to conventional farming (Sanders and Hess, 2019).

Also, the study on DWA (DWA, 2025) reported a reduction in NO_3^- leaching following the conversion from conventional to organic farming, based on several case studies.

On the other hand, it was stated that OF systems with a high share of legumes, which might supply N during periods without plant demand, can enhance NO_3^- leaching (Djurhuus and Olsen, 1997; Olesen et al., 2009; Reinsch et al., 2018b). Above this, the generally lower N efficiency of organic fertilizers and hardly calculable time of N release from mineralization might increase the risk of N leaching in OF systems, as shown in several studies (Torstensson et al., 2006; Di and Cameron, 2012; Sieling and Kage, 2006; Kühling et al., 2021; Frick et al., 2022). In addition, organic farms usually have lower yields and, consequently, lower crop N uptake, leading to higher product-related N leaching than on conventional farms. In contrast, N leaching per area might be lower (Biernat et al., 2020). DWA (2025) noted that management practices on organic farms are decisive for the risk of NO_3^- leaching. In particular, the share of legumes, the timing of plowing down legumes, and the intensity of soil tillage are known to be crucial factors. Therefore, the management factors of OF systems have to be optimized to reduce the risk of NO_3^- leaching (DWA, 2025).

Previous meta-studies showed that the comparison of NO_3^- leaching between organic and conventional farming systems is very challenging due to the following reasons: available data basis was not comprehensive, the quality of existing studies was often not sufficient, the comparability between both management systems was not given, crop rotations were not typical for the corresponding management system, or the whole crop rotation was not considered but only one part of the crop rotation. Another reason is that there is no comparable reference system for conventional systems, and the individual cultivation methods show great diversity. In this study, for the conventional system, "best management practices" following the principles of integrated farming were used (Diercks and Heitefuss, 1990). Integrated farming systems are sustainable systems that align economic requirements with ecological requirements by using best environmentally practiced crop production, plant nutrition, and plant protection, such as pest management at the absolutely necessary extent (damage threshold), plant-demand-driven fertilization, reduced soil tillage, and others (Diercks and Heitefuss, 1990). The principles of integrated farming systems today represent the modern status quo of conventional farming and are prevalent in Germany.

To evaluate the NO_3^- leaching potential of organic and conventional farming systems, long-term lysimeter studies under defined management practices and soil properties are a helpful tool. From the point to the regional scale, a lysimeter is the smallest unit representing a comprehensive view of processes in terrestrial systems and is widely used to study solute transport and water flow in soils (Zacharias et al., 2011).

The objectives of the present long-term lysimeter study were to quantify NO_3^- leaching from a loamy sandy soil under conventional and organic farming management treatments and to evaluate the N efficiency of both farming systems (conventional and organic) by examining yields, N uptake, and N balances. We hypothesized that:

i. Both farming systems show differences in total NO_3^- leaching, with lower NO_3^- losses in the organic farming system due to lower N inputs and higher N efficiency, and.

ii. The organic farming system has higher seepage amounts due to improved soil structure, due to organic input, and integration of legumes in the crop rotations.

Furthermore, we assume that:

iii. Both farming systems have different seasonal patterns of NO_3^- leaching because of different main factors affecting NO_3^- leaching (e.g., time of plowing down legumes).

The study aimed to optimize management practices for both farming systems (conventional and organic) to reduce NO_3^- leaching.

2 Materials and methods

2.1 Lysimeter and soil properties

For the study, lysimeters were managed agriculturally largely in line with the principles of OF according to the regulations of the European Union (EC, 2007; EU, 2018b) and conventional farming management according to the principles of best management practice (BMP). This long-term lysimeter study was carried out at the site Falkenberg of the Helmholtz Centre for Environmental Research GmbH (UFZ) (Germany, Saxony-Anhalt, Altmark) (coordinates 52.859780 N, 11.812595 E). Climatically, the lysimeter site was assigned to the temperate zone of central Europe, within the transition zone between maritime and continental climates. The lysimeter station was equipped with a meteorological station. The average annual precipitation was 557.8 mm (1991–2022; Falkenberg), with the highest amounts occurring in June and July. The average annual temperature was 9.6 °C, with a range of 7.3 °C to 11 °C (1991–2022) and occasional winter frost.

The long-term lysimeter study (32 years) was conducted from May 1991 to April 2023 and based on data from 23 non-weighing gravity-flow (free drainage) lysimeters (NWLYS). The management of the lysimeters remained unchanged throughout the entire 32-year period. The simple NWLYS type was often used in Germany and other central European countries for applied research on land management and its impact on drainage water quantity and quality (Lanthaler and Fank, 2005; Weihermueller et al., 2007). Square steel lysimeter casings (100 × 100 × 125 cm, 0.5 cm thick) were used for the lysimeter studies. After installing the vessels at the lysimeter facility, a 25-cm-thick filter layer (sand over gravel over stone gravel) was placed at the bottom. A drainage pipe (inner diameter 63 mm) was installed within the filter layer to collect seepage and discharge it into a leachate storage tank located in the lysimeter cellar (Bednorz et al., 2016; Meissner et al., 2010). The lysimeter vessels were filled with soil material from an agricultural site located 15 km to the west in 1981. Loamy sand (LS) soil type was used for this lysimeter experiment. The soil profile was mined separately into topsoil (0–30 cm) and subsoil (31–100 cm) at the extraction site and transported to the Falkenberg lysimeter station. To replicate the original soil structure of the sites, the soil profiles were manually reconstructed in the lysimeter vessels, mainly in a profile-compliant fashion. After this filling procedure, the lysimeters were irrigated to accelerate the settlement process (approximately 100 mm of irrigation water per year). When interpreting the results, it must be noted that the lysimeters, with a depth of 1.25 m, did not capture the entire root and capillary elevation range of the plant stock. Cameron et al. (1992) showed that edge flow of water and dissolved substances between the soil body and the lysimeter housing can lead to significant errors in the measurement of hydraulic conductivity and leaching rates. To avoid these marginal effects, the sidewalls of our lysimeter vessels were coated with a bituminous paint and sanded. The lower boundary condition of our NWLYS is a seepage-face boundary through which only water at soil saturation can escape. Interrupting the capillary connection to deeper soil layers impairs drainage and prevents capillary rise. A seepage-face boundary condition can lead to distortions in seepage (Stenitzer and Fank, 2007) and nutrient loads (Abdou and Flury, 2004; Boesten, 2007). Despite the NWLYS's one-sided systematic error, a comparison of the OF and BMP land management systems is possible. The soil properties of the lysimeter fill soil are shown in Table 1.

TABLE 1 Physical and chemical properties of the lysimeter soil.

Soil properties	Soil depth (cm)	
	0–30	31–100
Soil type	Stagnosol (pseudogley)	
Texture	Strong loamy sand	Slightly loamy sand
Dry matter density (g/cm³)	1.48	1.84
Field capacity (vol.%)	28	22
Effective field capacity (vol.%)	15	11
pH	5.8	5.6
Total carbon content (%)	1.13	0.17
Total nitrogen content (%)	0.13	0.04
Calcium carbonate (%)	0.4	0.3
Double lactate extractable phosphorus (mg/100 g soil)	11.5	1.1
Potassium (mg/100 g soil)	19.5	7.0

2.2 Cultivation of the lysimeter soils

Table 2 provides an overview of the different agricultural management systems for arable land and the associated fertilizer applications. In accordance with the objective of this study, two cultivation systems, differing in integrated crop types, were compared. Manure was applied in both systems in liquid or solid form. The cultivation was typical of agricultural production in reunified Germany in 1991, while fertilization was more experimental. Both mineral and organic fertilizers were used on lysimeters managed in accordance with BMPs according to the principles of integrated farming systems (Diercks and Heitefuss, 1990). In contrast, only organic fertilizers were applied at the OF lysimeters. In our lysimeter study, we used catch crops such as a mixture of maize and sunflowers, which were harvested in late autumn and removed from the lysimeters in both OF and BMP. OF's crop rotation included clover and catch crops to meet the requirements of European agricultural policy, subsidies from the Common Agricultural Policy, and governmental aid. The established crop rotations have been maintained since this time. The significant differences in N fertilization levels between the OF and BMP experimental agricultural management systems are due to the experimental design, which was intended to differentiate the two systems clearly.

Nitrogen was fertilized at BMP in the form of calcium ammonium nitrate (CAN, 26% N, 10% Ca). The granulated

TABLE 2 Overview of the experimental lysimeter management practices and fertilization (W. = winter).

Designation experiment	Number of lysimeters	Crop rotation	Mineral N-fertilization (kg ha^{-1})			Organic N-fertilization (kg ha^{-1})		
			N	P	K	N	P	K
Organic farming (OF)	12	W. wheat and catch crop	0	0	0	80[a]	14[b]	160
		Pea and catch crop	0	0	0	0	0	0
		W. wheat and catch crop	0	0	0	80	14[b]	160
		Oats and clover grass underseed	0	0	0	0	0	0
		Clover grass	0	0	0	0	0	0
		Potatoes	0	0	0	150[c]	90	180[d]
Best management practice (BMP)	10	W. wheat and catch crop	145	20	150	0	0	0
		Potatoes	120	20	150	150	90	180
		W. barley and catch crop	145	20	150	0	0	0
		Maize	100	20	150	0	0	0
		Sugar beets	80	20	150	125	75	150

Phosphorus and potassium fertilization was estimated according to LLG (2019).

[a] Beef liquid manure.

[b] Farmyard manure, P-content 1–3.1 kg P t^{-1}.

[c] Manure from cattle, N-content 5–6 kg N/t.

[d] Farmyard manure, K-content 4.7–7.8 kg K t^{-1}.

fertilizer was annually spread (treatments according to the BMP management schedule) in spring, based on the crop development stage. Crop protection products (herbicides, fungicides, insecticides, and others) were not used on the lysimeters. Annual soil tillage was carried out, followed by seedbed preparation. The crop residues were tilled into the soil after harvest, and weeds were mechanically controlled by tilling with a cultivator.

The lysimeters were irrigated from 1991 to 2003 to meet plant physiological needs and maximize yield. Depending on crop and specific climate conditions, irrigation water was additionally applied. This irrigation regime was changed in 2004. From this date onward, the crops were irrigated exclusively to safeguard plant stocks, resulting in a significant reduction in the amount of irrigation water applied (up to 50 mm annually) (Rupp et al., 2021).

The BMP variant had the following crop rotation: winter wheat + catch crops (oil radish), potatoes, winter barley + catch crops (oil radish), maize, and sugar beet. The following crop rotation was used for the OF variant: potatoes, winter wheat + catch crops (maize/sunflowers), field peas + catch crops (maize/sunflowers), winter wheat + catch crops (maize/sunflowers), oats + clover grass underseed, and clover grass. BMP was primarily fertilized with mineral fertilizers, while the organic variant was fertilized with farmyard manure and beef liquid manure (Strauss et al., 2013). The lysimeter experiment involves comparing different land management systems. Due to the legally defined framework for OF, OF and BMP treatments differed across crop types and management practices.

2.3 Leachate sampling, water analyses, and assessments

Depending on climatic conditions, leachate occurred in the lysimeters mainly from November to April. The leachate was continuously collected in storage tanks (two polyethylene canisters, each with a volume of 30 dm^3) in the lysimeter cellar. The amount of leachate was determined by weighing the leachate storage tanks monthly. Monthly samples were taken, filtered through 0.45 μm Millipore syringe filters, and analyzed in the UFZ facility laboratory for concentrations of inorganic N (nitrite NO_2-N, NO_3^--N, and ammonium NH_4-N), according to German Industrial Standards (DIN 38405–38406) by ion-exchange chromatography (IC, Thermo Fisher Scientific, Idstein, Germany).

Atmospheric deposition was determined using a bulk precipitation sampler, BUS 100, from Eigenbrodt (Hamburg, Germany). As the measuring device lacked an active cooling system, the rainwater collected by the device was extracted after significant rainfall events and stored in a container in the laboratory building at 8 °C. Here, too, monthly samples were prepared and analyzed according to the chemical methodology described.

The primary data collected were secured, and all work carried out and observations were fully documented. Uniform measurement methods were used to determine the relevant quantitative and qualitative parameters for all lysimeters included in the lysimeter test. In 1993, the determination of NO_3^--N, NO_2-N, and NH_4-N was switched from the photometric method to ion-exchange chromatography. Extensive parallel measurements were conducted to ensure comparability of the results. The analyzers used were serviced and checked annually by the manufacturer's service staff. In addition, the quality of the analyses was assured through participation in round-robin tests with other laboratories.

We calculated monthly loads from monthly N concentrations and seepage water volumes, which were then used to estimate average annual N concentrations and annual loads (seepage-weighted averages). Seepage-weighted annual nitrogen concentration values were calculated as the quotient of the annual sum of nitrogen loads (monthly values) and seepage (over the same period).

The total N content of the harvested material was determined by dry combustion (elemental analysis) according to DIN ISO 13878 using a Vario EL cube (Elementar Analysis Systems, Langenselbold, Germany).

The N supply from organic fertilization was calculated based on annual chemical analyses of the fertilizers used (liquid manure, slurry, and farmyard manure). Annual N balances were calculated based on the applied N fertilization, the determined N contents in the harvested crop, the atmospheric N deposition, the measured N loads, and the N uptake by the cultivated plants. For the lysimeters cultivated according to the OF system, N fixation by the cultivated legumes was estimated from the literature (Bischoff, 2014; Loges, 2013; Schimpf et al., 2019) and included in the balance calculation. Gaseous N losses were not measured in this study and were therefore not included in the N balance. The study by Pietzner et al. (2017) showed that N losses via N_2O and NH_3 emissions were very low (<1 kg N/ha).

The N use efficiency (NUE), defined as the ratio of N taken up to the N applied to the crop, was calculated according to Martinez-Feria et al. (2018) as indicated in Equation 1. The calculation is based on median N uptake of cultivated plants in the OF and BMP cropping regimes (annual averages) versus N supply (sum of fertilization, atmospheric deposition, biomass uptake, and seed inputs) in individual years. For the calculation of N input by N fixation (legumes) and for inputs with seeds, literature references (Bischoff, 2014; Loges, 2013; Schimpf et al., 2019; Naegle et al., 2005) as indicated in Equation 1.

$$NUE = \frac{Nuptake}{Nsupply} \tag{1}$$

2.4 Statistics

Data assessment was performed using OriginPro 2024 software (OriginLab Corporation, Northampton, USA). The available data were checked for normal distribution. As this was not the case, the available time series were statistically compared using the Kruskal–Wallis test (one-way ANOVA on ranks with Dunn's test for statistical significance), a non-parametric method used to test whether lysimeter data originated from the same distribution. The available measurement series were compared using median values.

Due to the experimental design, there were only two replications per treatment for each crop rotation element in the OF and BMP management variants. Natural variability is only partially represented due to the small number of repetitions.

Long-term studies (Teuling, 2018) have shown that only these allow for reliable conclusions regarding the effects of land use and land-use changes, despite the occurrence of dry and wet years, which significantly influence soil moisture and evaporation. Time series analyses of the N leaching data (OF and BMP) for the 32-year long-term series were performed with OriginPro 2024 with the provided Apps "simple time series analysis (v. 1.20)" and "advanced time series analysis (v. 1.00)" to proof data series of stationarity, existing trends (linear regression), and autocorrelation (ACF, PACF, ARIMA) and to identify seasonal variations of long-term data series. Thus, time series analyses were used to retrospectively examine long-term data to detect seasonal patterns and the structure of the time series.

3 Results

3.1 Seepage

Figure 1 shows the monthly seepage volumes measured for the OF and BMP treatments during the study period from May 1991 to April 2023. Over the entire study period, the cumulative seepage water volume (median) was 3,518.9 mm at OF and 2,702.5 mm at BMP. The mean amount of seepage at the variant OF (9.8 mm) differed highly significantly from the amount of seepage in the BMP treatment, which was lower at 8.2 mm. Due to the many months without seepage, especially during the growing season, a median value of 0 mm was determined for both treatments.

The result of a time-series analysis (decomposition) that included all experimental years showed almost identical behavior for both treatments (Supplementary Figure 1). Seepage occurred mainly from September to January (of the following year). However, in the case of OF, there was a more intense seepage formation in September compared to the BMP treatment. The individual values for seepage at OF showed very little fluctuation between June and November and were therefore highly concentrated. In contrast, the trend-adjusted variation of the individual values was greatest in December, January, and February. At BMP, March to July showed exceptionally low variation, while September to November showed high variation.

The seepage for OF showed no significant differences, particularly in adjacent months. This pattern was also generally observed for BMP, although considerably more months showed seepage that did not differ significantly (Supplementary Table 1).

3.2 N concentration

The measured seepage-weighted monthly N concentrations for both management treatments are shown in Figure 2. The range of N concentrations measured was extensive, ranging from 0 to 294 mg N L^{-1} for OF and from 0 to 249 mg N L^{-1} for BMP. Peak N concentrations were reached for OF in February 1992, after the establishment of organic farming (following a previous intensive cultivation with a cereal-field fodder crop rotation from 1984 to 1990), and for BMP in January 2020, after the resumption of seepage at the end of the dry years 2018 and 2019. There were no statistically significant differences regarding N concentration between the medians of OF and BMP at 22.8 and 25.4 mg N L^{-1}.

The time-series analysis showed decreasing N concentrations from January to April for both treatments (Supplementary Figure 2). In OF, N concentrations tended to be high in July. From August to December, N concentrations showed a decreasing trend. For BMP, higher N concentrations occurred in June, which showed fluctuations in the following months before reaching the lowest values in November and December.

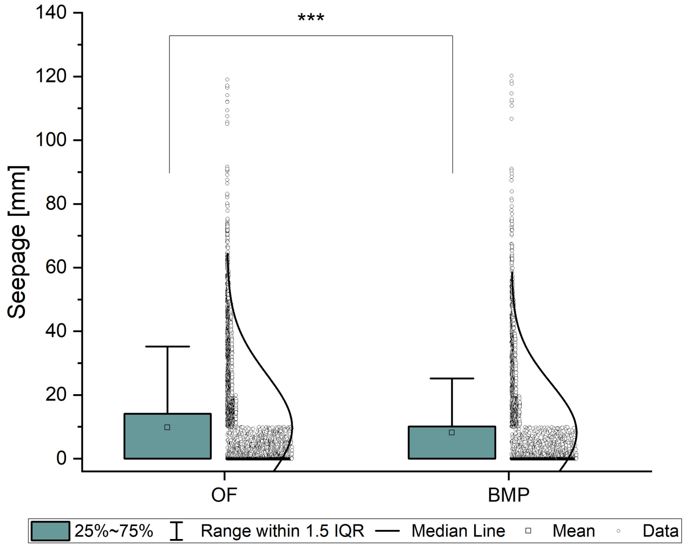

FIGURE 1
Boxplot and frequency distribution of seepage in organic farming (OF) and best management practice (BMP) for the study period 1991–2023 (asterisk with bracket as a significance mark). ***$p<0.001$.

The N concentration data for OF showed comparable variation across all months, with June and July data closer together. The BMP data showed similar behavior. However, the data for April and June exhibited the least variation.

The N concentration for OF showed no significant differences in adjacent months. Furthermore, N concentrations in January to May showed no significant differences. This pattern was also observed for BMP, although there were significantly more months with non-significant differences (Supplementary Table 2).

3.3 N load

Figure 3 shows the calculated annual N loads. The Kruskal–Wallis ANOVA revealed significant differences in median annual N loads between the OF and BMP treatments. Over the entire trial period, a total N load of 883.1 kg N ha^{-1} (median) was observed for the OF treatment. For the BMP treatment, the total N load was 833.6 kg N ha^{-1} over the same period, which was 49.5 kg N ha^{-1} lower than for the OF treatment. In the OF treatment with 26.1 kg ha^{-1}, a significantly higher annual N load (median) was calculated compared with BMP (20.5 kg ha^{-1}). Loads exceeding 108.6 kg ha^{-1} for the OF treatment were considered outliers. For BMP, this value was 111.6 kg ha^{-1}. Accordingly, numerous outliers occurred in both treatments. Particularly striking was 2020 for BMP, when this value was exceeded in 4 out of 10 lysimeters. The maximum values for both treatments were comparably high at 297.9 kg ha^{-1} (OF) and 288.6 kg ha^{-1} (BMP).

The results of a time-series analysis (Supplementary Figure 3) showed almost identical behavior for both treatments. Increased N

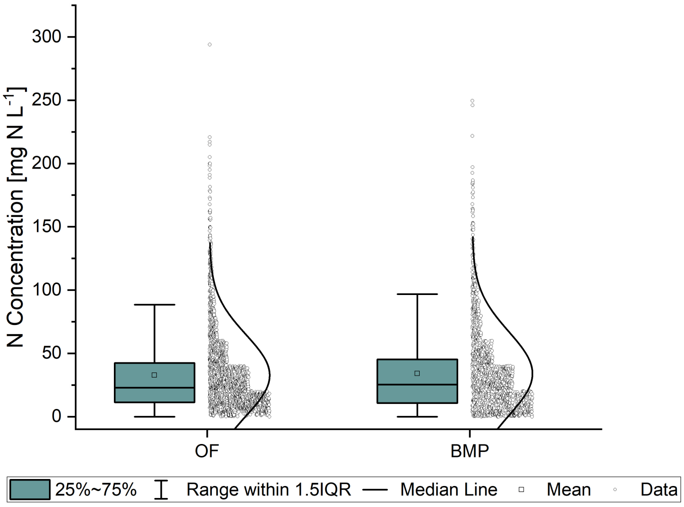

FIGURE 2
Boxplot and frequency distribution of N concentration in organic farming (OF) and best management practice (BMP) for the study period 1991–2023 (asterisk with bracket as a significance mark).

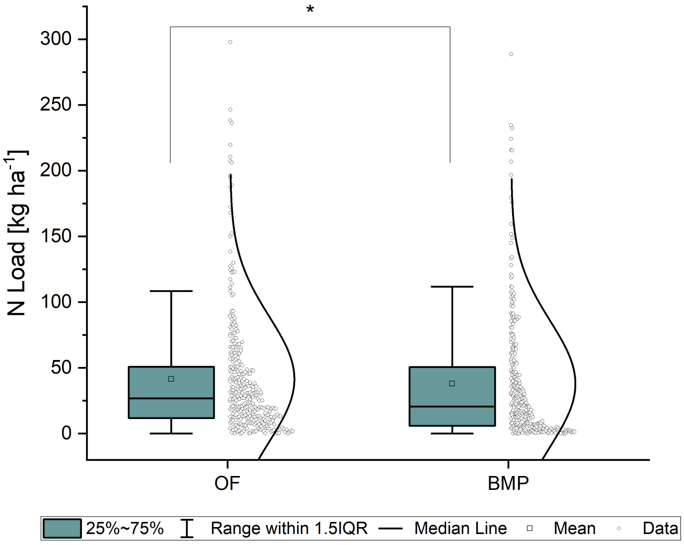

FIGURE 3

Boxplot and frequency distribution of annual N load in organic farming (OF) and best management practice (BMP) for the study period 1991–2023 (asterisk with bracket as a significance mark). *p<0.05.

loads occurred in both treatments, primarily during September to November. N loads tended to be lower during December to June. In contrast, higher N loads were noticeable in the OF variant in July and August. The trend-adjusted monthly values for N load showed little variation in January and February. Particularly striking were the high variations in September and October, which also coincided with the highest monthly N load values. A similar pattern occurred at BMP. The N loads of OF and BMP showed a pattern comparable to that of the N concentrations, with non-significant differences between adjacent months, as already described in Section 3.2 (Supplementary Table 3).

3.4 Dry matter yield

The measured dry matter yields of the two treatments are presented in Figure 4. The medians of OF and BMP showed highly significant differences, as determined by the Kruskal–Wallis ANOVA. For example, over the 32 trial years, BMP achieved a significantly higher level of mean dry matter yield of 157.6 dt ha^{-1} compared to 102.0 dt ha^{-1} for OF. The higher yield level of the crop rotation (cf. Table 2) and management in BMP is also reflected in the measured yield maxima, which were 533.2 dt ha^{-1} in BMP compared to 364.3 dt ha^{-1} in OF. The differences

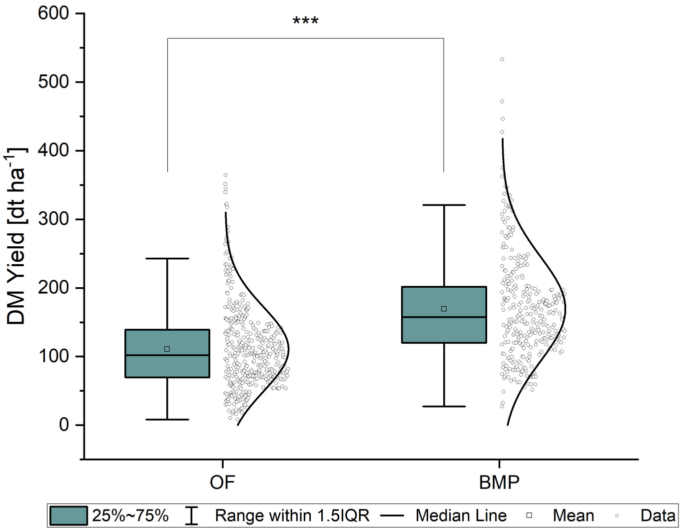

FIGURE 4

Boxplot and frequency distribution of annual dry matter yield in organic farming (OF) and best management practice (BMP) for the study period 1991–2023 (asterisk with bracket as a significance mark). ***p<0.001.

between the OF and BMP treatments are due to the cultivation of different crop types. For example, sugar beets were included in the crop rotation in the BMP treatment, whereas they were absent in the OF treatment.

3.5 N uptake

The N uptake by the growing plants in the OF and BMP treatments, presented in Figure 5, also showed highly significant differences. Based on our long-term studies, the mean N uptake in OF was 132.9 kg ha^{-1}. In contrast, the mean N uptake in BMP was 178.2 kg ha^{-1}. This result, taking into account differences in crop rotation, is consistent with the yield assessments for both treatments.

3.6 N balance and N use efficiency

Relative N balance for OF and BMP based on median values of fertilization, atmospheric deposition, biomass uptake, and leaching in individual years for the 1991 to 2023 experimental period is presented in Figure 6. For the nitrogen balance, the mean annual atmospheric (wet and dry) N deposition of 8.3 kg ha^{-1} measured at the lysimeter station site was taken into account. The crop rotation of the OF lysimeters included oats with a clover-grass undersow and, in the following year, clover grass as the main crop. Furthermore, field peas were integrated into the crop rotation. Our own investigations on leguminous N-fixation were not available. The literature reports an annual legume N fixation of approximately 400 kg ha^{-1} (Loges, 2013). In the collection of fertilizer law guidelines of the German federal state of Saxony-Anhalt, a symbiotic N fixation of 230 kg ha^{-1} was set as binding for the cultivation of clover grass (Schimpf et al., 2019). When growing field peas, it is assumed that 150 kg ha^{-1} remains usable for the subsequent crop (Bischoff, 2014). These amounts of nitrogen have to be considered in the N balance. Clover grass and field peas were cultivated in a rotation of 6 years. Thus, an annual balance input of 63.3 kg N ha^{-1} (38.3 for clover grass and 25 kg N ha^{-1} for field peas, respectively) was included in the yearly balancing for OF.

The balance of N inputs (fertilization, legume N-fixation, and atmospheric input) and N outputs (plant uptake and leaching) showed a clearly negative N balance for the OF treatment in the first 20 years since experimental conversion. Subsequently, balance surpluses of up to 41.8 kg N ha^{-1} occurred in 2012, 2014, 2015, 2016, 2018, 2019, 2020, and 2021.

For the experimental treatment BMP, the N balance remained negative (except for small surpluses in 2003, 2004, 2013, and 2017). In contrast to the OF treatment, the nitrogen balances for the BMP showed a lower tendency toward balance surpluses over the last 10 experimental years.

Regarding NUE, the treatments did not differ significantly. The median NUE values were identical for both treatments, at 1.09 (OF) and 1.01 (BMP). Notably, the N efficiency of the OF treatment exceeded 1.4 during the first 11 years after the establishment of management under OF principles (Figure 7). Thereafter, the coefficients showed a decreasing trend, with values ranging from 0.56 to 1.16.

In contrast to the OF treatment, BMP treatment showed a relatively uniform level of N efficiency. The calculated coefficients, which ranged between 0.71 and 1.36, exhibited a relatively consistent level without any discernible trend.

4 Discussion

4.1 Seepage

The plant stands on the lysimeters managed according to OF principles were less developed than those managed according to BMP due to the lower nutrient supply. This effect was already described by Mäder et al. (2002). Seepage flux was found to be

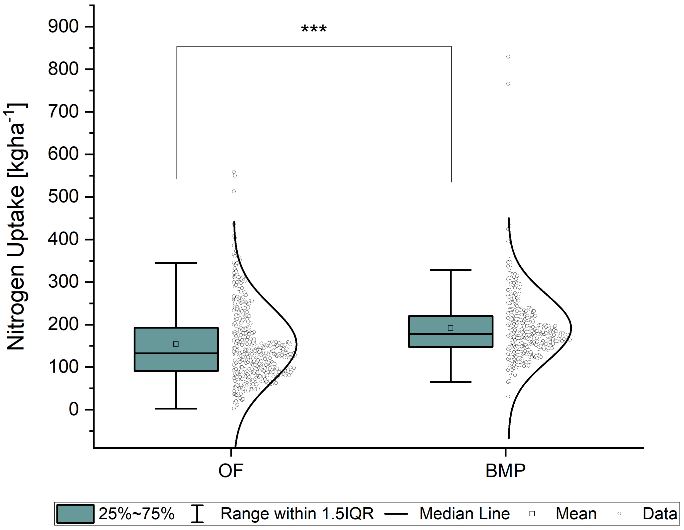

FIGURE 5
Boxplot and frequency distribution of N uptake in organic farming (OF) and best management practice (BMP) for the study period 1991–2023 (asterisk with bracket as a significance mark). ***p<0.001.

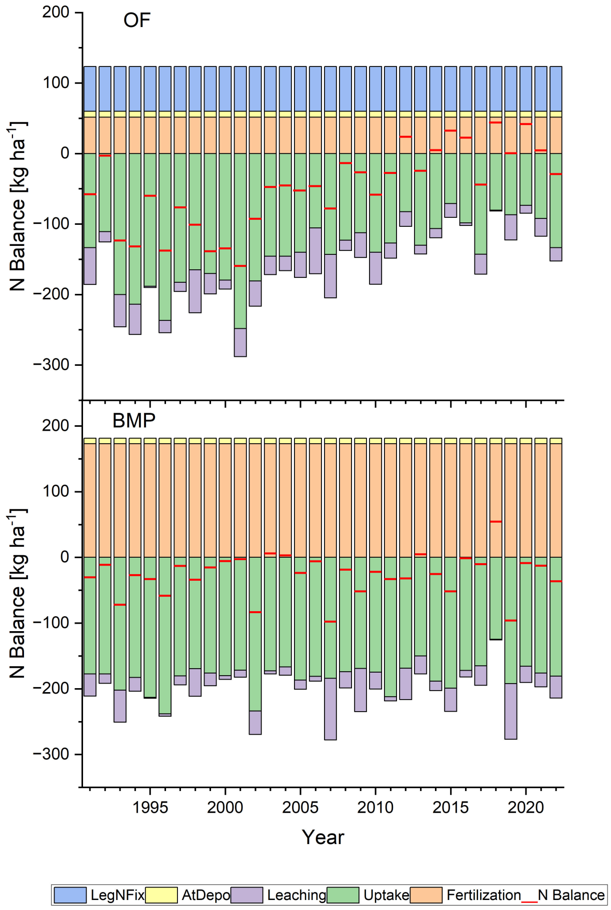

FIGURE 6
Relative N balance for OF and AM based on median values of fertilization, atmospheric deposition, biomass uptake, and leaching in individual years (literature references for N fixation by legumes) for the 1991 to 2023 study period.

mainly controlled by evaporative demand, precipitation, and land cover type (Zhang et al., 2015). Accordingly, less water was lost to evapotranspiration and reached the infiltration zone, resulting in higher seepage fluxes under OF than under BMP. This effect was observed throughout the study period, except during the first 5 years after land-use conversion. This statement is also supported by the time-series analysis, which showed more intensive seepage formation in September, with the maximum already occurring in October at OF, i.e., 1 month earlier than in the BMP treatment.

Furthermore, compared with conventional farming, other studies have shown that OF also increased mesoporosity (pores with diameters of 5–500 μm) and cumulative water infiltration (Blanco-Canqui et al., 2024). Papadopoulos et al. (2014) reported that OF increased the mesopore percentage. Furthermore, increased infiltration was observed under OF due to higher organic carbon and aggregate stability, as well as the use of diversified cropping systems (i.e., deep-rooted species) relative to conventionally managed systems (Williams et al., 2017). The authors further emphasize that organically farmed soils receiving high levels of animal manure for multiple years can have higher water infiltration rates than soils under conventional farming. Another study showed that OF can maintain and improve soil structure over the long term. The result is a soil with a topsoil that is conducive to plant growth (Gerhardt, 1997).

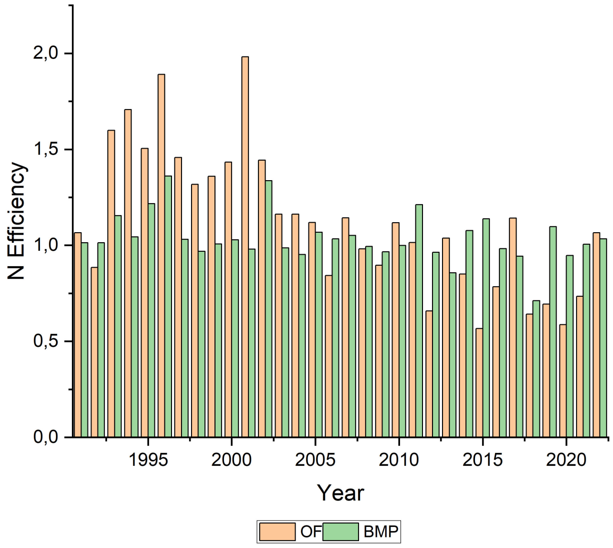

FIGURE 7
N efficiency for OF and BMP based on median values of biomass uptake versus N supply (sum of fertilization, atmospheric deposition, and input with seeds) in individual years (literature references for N fixation by legumes and input with seeds) for the 1991 to 2023 study period.

4.2 N concentration and N load

The mean N concentrations clearly exceeded the WHO limit value for drinking water of 50 mg NO_3^- L^{-1} (11.3 mg N L^{-1}) (WHO, 2002) and the limit value for groundwater of the Water Framework Directive (WFD) (EU, 2000) in both experimental treatments. In the lysimeter leachate managed according to the OF principles, peak N concentrations exceeding 60 mg N L^{-1} occurred, especially following potato cultivation after a dry year (with a previous clover grass cultivation plowed under in October). Potatoes are known to be crops that require intensive tillage at harvest, which may favor mineralization. Also, in other studies, it was observed that the rewetting of soil after long periods of dry weather can trigger a flush of N mineralization from accumulated N in the topsoil, leading to temporarily high NO_3^- leaching (Spiess et al., 2020). The seasonal analysis of N concentrations in BMP shows a relatively balanced regime across the individual months.

In contrast, in OF, elevated N concentrations occurred as early as the summer months, indicating leaching of previously mobilized N. When managed according to OF, N surpluses occurred that could not be used by cultivated plants. Above all, the surpluses resulting from the mineralization and mobilization of previously symbiotically bound nitrogen prevented a significant reduction in N concentrations in the OF treatment compared to the BMP treatment. Comparable patterns of increased N concentrations could not be demonstrated under conventional management without the cultivation of legumes. Increased N leaching after early autumn plowing was also reported in other studies (Djurhuus and Olsen, 1997; Hansen et al., 2020; Kayser et al., 2008). Therefore, it was suggested that clover grass or other legumes should be plowed in late winter or spring, when mineralized N can be utilized by crops (Djurhuus and Olsen, 1997; DWA, 2025). In addition, reduced soil tillage intensity was proposed to minimize NO_3^- leaching by avoiding mineralization peaks (DWA, 2025; Spiess et al., 2020). In the present study, the soil tillage intensity was high and should be minimized in the future to reduce NO_3^- leaching.

The use of exclusively organic fertilizers can also lead to higher N concentrations and, consequently, increased N leaching losses. Comparable results with higher cumulative N leaching in variants with organic fertilizers compared to mineral fertilizers have also been confirmed in other studies (Di and Cameron, 2012; Sieling and Kage, 2006; Kühling et al., 2020). The reasons for this are the lower N efficiency of organic fertilizers compared with mineral fertilizers and the difficulty of timing N release through mineralization, which increases the risk of N leaching (Bergström and Kirchmann, 2006; Frick et al., 2022). Thus, an enhancement of N efficiency of organic fertilizers by technical and chemical solutions was proposed as one decisive management measure to reduce NO_3^- leaching (Quemada et al., 2013).

The influence of organic versus conventional management on N leaching is controversially discussed in the literature, since a variety of factors (including climate, soil characteristics, crop yield, proportion of legumes, soil tillage, organic farming with or without livestock) can have an influence here (Knudsen et al., 2014, Knudsen et al., 2006; Biernat et al., 2020). A previous meta-study on N leaching in organic and conventional farming (61 studies in total) showed considerable variation in individual findings (Sanders et al., 2025). The included studies varied widely in their comparability and system representation, and thus, their informative value was limited in some cases. The authors of the meta-study concluded that OF reduced N leaching by 26% (median) compared to conventional farming. However, this study also noted that the observed high heterogeneity in the results was due to the variability of the agricultural systems studied. There is no comparable reference system, and the individual cultivation methods show great diversity, particularly in conventional agriculture. Whereas OF has clear boundaries set by the European Regulation (EU, 2018a), there is no corresponding unified framework for conventional farming. Numerous European studies have documented lower N leaching in OF compared to conventional farming and attribute the reduction mainly to lower N inputs and the cultivation of catch crops (Stopes et al., 2002; Benoit et al., 2016; Hansen et al., 2020). In the present lysimeter study at the Falkenberg site, non-legume catch crops after winter cereals and grain peas were integrated into the crop rotations in both treatments, OF and BMP. Over time, no influence of catch crops on N leaching reduction in July, August, September, and October could be demonstrated, as reported in other studies (Beisecker and Seith, 2021). The reason for this is a multitude of other influencing factors. As already discussed, another reason for comparable N concentrations and leaching losses in OF and BMP is the high proportion of legumes (clover grass, grain peas) in the OF crop rotation. The literature also points out that the cultivation of clover grass in particular, as one of the most important fruits in livestock-less organic farms for the provision of N for the main crops, also carries a high risk of N leaching due to the possible high N supply in times when the plants do not need N (Djurhuus and Olsen, 1997; Olesen et al., 2009; Reinsch et al., 2018a). Field peas can biologically fix 150–300 kg N ha^{-1}, while 40–150 kg N ha^{-1} is available to the subsequent crop (Bischoff, 2014). Due to the high risk of biologically fixed N leaching after the cultivation of field peas, it has been suggested to combine grain legumes with the cultivation of undersown crops (DWA, 2025).

In addition, organic farming systems usually yield lower amounts than conventional cultivation and are therefore also considered less economically efficient (Seufert et al., 2012; Shah et al., 2017; Biernat et al., 2020). Biernat et al. (2020) reported lower N leaching in livestock-free organic farming systems than in conventional farming.

The exceptionally high N concentrations and loads measured in 2020 are considered a consequence of the extreme droughts in 2018 and 2019. Under the climatic conditions in northeastern Germany, seepage fluxes were disrupted in these dry years. The recurrence of seepage was associated with exceptionally high nitrogen concentrations and leaching losses (Rupp et al., 2021).

The seasonal analysis of N concentrations in BMP shows a relatively balanced regime across the individual months. In contrast, in OF, elevated N concentrations occurred already in the summer months independent of fertilization events, indicating a leaching of previously mobilized N from the organic N pool. This was also reflected in the temporal analysis of N loads. When managed according to OF, N surpluses occurred that could not be used by cultivated plants.

A trade-off exists between the observed increase in seepage fluxes and the simultaneous increase in N loads at OF. Increased fluxes toward the groundwater positively influence the water balance under the climatic conditions of northeastern Germany. On the other hand, increased load of dissolved nitrogen compounds into groundwater, which negatively affects water quality, cannot be ruled out in the case of OF.

When assessing the current lysimeter study at the Falkenberg site, however, it should also be noted that the integrated treatment did not necessarily correspond to a conventional management method. The integration of cover crops into a comparatively broad crop rotation and low nitrogen balances had a positive effect on water protection.

4.3 Dry matter yield, N balance, and N efficiency

Based on long-term median values, our lysimeters treated according to OF achieved 64.7% of the dry matter yield of the conventionally managed lysimeter (BMP), despite the absence of synthetic chemical pesticides and mineral fertilizers. This aligns with the results of a meta-analysis comparing yields from organic and conventional farming systems worldwide (Seufert et al., 2012). The analysis of available literature data shows that, overall, organic yields are typically lower than conventional yields. Nevertheless, these yield differences are highly contextual, depending on system and site characteristics, and range from 5% lower organic yields (rain-fed legumes and perennials on weak-acidic to weak-alkaline soils), 13% lower yields (when best organic practices are used), to 34% lower yields (when the conventional and organic systems are most comparable). Another meta-analysis came to comparable results. Here, yields under organic farming were, on average, 25% lower than those under conventional farming, resulting in a 30% yield gap for cereals (Alvarez, 2022). For German farms, the yield difference between organic and conventional farming was 40% across all crops (DWA, 2025).

The average N balances of both treatments (balancing without consideration of gaseous N losses, = brutto N balances) were relatively low with −47.6 (−165.1 to +41.8) kg N ha^{-1} for OF and −19.2 (−95.6 to +55.7) kg N ha^{-1} for BMP (see Figure 6), indicating a high N efficiency by uptake of excessive fertilizer N by main crops and catch crops as also seen by the calculated NUE (1.09 for OF and 1.01 BMP). These high NUE figures suggest a decline in soil fertility and soil mining, respectively (EU Nitrogen Expert Panel, 2015). Target values for an optimal NUE were given as 0.7–0.9 to avoid the risk of N losses at one site and a reduction in soil fertility at the other site (EU Nitrogen Expert Panel, 2015). In contrast to the OF lysimeters, intensive management under BMP and a high mineral N fertilization rate were assumed to be less N-efficient than OF in this study. However, it should be noted that gaseous N losses from the application of organic fertilizers were not accounted for and could result in lower NUE values for OF. Nevertheless, no significant differences in NUE were observed between the treatments. In contrast, Chmelíková and Hülsbergen (2019) found that in 42% of the considered organic farms, N efficiencies were higher than those of conventional farms, whereas 37% had comparable N efficiencies, and 21% had lower N efficiencies than conventional farms.

The N balance of the OF lysimeters showed an increasing trend from around the 16th year of the study, driven by declining dry matter yields, indicating a decline in N use efficiency of the cultivated crops. In contrast, this trend was not observed in the BMP lysimeters. Especially in organic farming, a significant challenge for sustainable land use is to improve N management (Tuomisto et al., 2012). Overall, the calculation of the N balance was fraught with uncertainties. On the one hand, symbiotic N fixation for OF use was estimated at 230 kg ha^{-1} based on the guideline values for the cultivation of clover grass, as outlined in the follow-up documents to the German Fertilizer Ordinance (Schimpf et al., 2019). Another reference reports 400 kg ha^{-1} under comparable conditions (Loges, 2013). Furthermore, for symbiotic N fixation in field peas, a value of 150 kg N ha^{-1} was used as the basis for the estimates (Bischoff, 2014). To quantify the mean annual atmospheric N input, we considered a value of 8.3 kg N ha^{-1}. Other authors determined for the experimental site an atmospheric N deposition of 10–41 kg N ha^{-1}, based on container tests using the ^{15}N dilution method (Böhlmann et al., 2005; Russow and Böhme, 2005; Russow et al., 2005).

5 Conclusions

Our long-term study comparing OF and BMP treatments showed that NO_3^- concentrations were not reduced by OF, and no significant differences were found between the two cropping systems. Given this, OF management needs to be optimized to reduce the risk of NO_3^- leaching. In particular, resolving the trade-off between the simultaneous increases in seepage fluxes and nitrogen loads poses a significant challenge with OF. To address this, several management strategies to reduce NO_3^- leaching with OF have been proposed, for example, avoiding plowing under legumes (alfalfa, clover) in autumn and instead plowing in late winter or spring to minimize mineralization, or shifting plowing to periods with higher plant nutrient requirements. Notably, both cropping systems exhibit distinct seasonal patterns of NO_3^- leaching due to their differing management practices, including plowing under legumes. Looking ahead, the main challenge for increasing OF's share in agricultural management systems is to enhance OF productivity by increasing yields and improving yield stability. Furthermore, to meet this challenge, the main drivers of nitrogen dynamics in the soil, as well as the complex processes that influence nitrogen release—such as soil carbon quality and the structural and functional composition of the soil microbiome—should be investigated in greater detail. Thus, process studies are essential for a comprehensive understanding of the complex soil processes that can lead to the storage and/or release of nitrogen compounds.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

HR: Methodology, Writing – original draft, Conceptualization, Supervision, Writing – review & editing, Investigation. NT: Writing – review & editing, Formal analysis, Investigation, Writing – original draft, Methodology, Validation. RM: Writing – review & editing, Funding acquisition, Formal analysis, Methodology, Conceptualization, Investigation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author HR declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2026.1764907/full#supplementary-material

SUPPLEMENTARY FIGURE 1
Seasonal analysis (base = 1 for multiplicative model) and boxplot for Trend-adjusted data by season of seepage in Organic Farming (OF) and Best Management Practice (BMP) for the study period 1991 – 2023.

SUPPLEMENTARY FIGURE 2
Seasonal analysis (base = 1 for multiplicative model) and boxplot for Trend-adjusted data by season of N concentration in Organic Farming (OF) and Best Management Practice (BMP) for the study period 1991 – 2023.

SUPPLEMENTARY FIGURE 3
Seasonal analysis (base = 1 for multiplicative model) and boxplot for Trend-adjusted data by season of N load in Organic Farming (OF) and Best Management Practice (BMP) for the study period 1991 – 2023.

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