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Nitrogen leaching from tile-drained fields and lysimeters receiving contrasting rates and sources of nitrogen

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Abstract

Leaching of nitrogen from arable land can lead to pollution of groundwater and surface water. Various measures have been implemented in agriculture to reduce leaching, but there is still potential to do more. To find the best agricultural management regime to limit the problem, leaching from soils under different management must be measured. Different methods to estimate leaching are available, but they have not been thoroughly evaluated. This study compared (a) leaching of nitrogen from five different fertilizer treatments differing in amount and source (mineral and organic) of nitrogen and (b) two different methods for measuring leaching (tile-drained field plots and lysimeters). Nitrogen leaching from five different fertilizer treatments was studied for three years in a tile-drained field facility and for three of the treatments also for 16 months in a lysimeter facility. Leaching from organic and mineral nitrogen sources was similar in the three-year field study. Mineral nitrogen input above the economic optimum tended to give greater leaching (by 24%–43%) than nitrogen input at the expected optimum. Measurements in lysimeters and tile-drained field plots gave similar results, although leaching values tended to be slightly higher (by 18%–25%) in the tile-drained field. Overall, both facilities give reliable estimates of nitrogen leaching and are suitable for leaching studies.

KEYWORDS

fertilizers, leaching, lysimeters, nitrate, nitrogen, tile drain

1 | INTRODUCTION

Leaching of nitrogen (N) from agriculture poses an environmental problem through pollution of groundwater and surface water and loss of a valuable resource from the production system. Nitrogen leaching is affected by natural processes and management. It depends on, for example soil texture, weather, crop, tillage, use of cover crops and the source, rate and timing of N inputs (Bergström, 1987; Bergström & Johansson, 1991; Bertilsson, 1988; Constantin et al., 2010; Goulding, 2000; Goulding et al., 2000). Within European Union member states, various policy measures have been introduced to reduce N leaching, for example economic incentives for growing catch crops, regulations preventing ill-timed distribution of manure and a threshold on annual N supply with organic fertilizers per hectare.

The effect of fertilizer N application on leaching depends on the amount of applied N taken up by the crop and removed with harvest. The efficiency of fertilizer use may be affected by, for example fertilizer rate and source of nitrogen (Delin

& Stenberg, 2014; Korsaeth & Eltun, 2000). Above the economic optimum, higher rates of fertilizer N increase the risk of N leaching, while up to the optimum, extra leaching induced by additional N application is very low (Constantin et al., 2010; Delin & Stenberg, 2014; Goulding et al., 2000). This is because of N uptake by the crop, which increases more with N input at rates below the optimum (Delin & Stenberg, 2014).

Organic sources, such as manure and slurry, generally have lower fertilizer efficiency than mineral fertilizers (Gutser et al., 2005). This does not necessarily result in more N leaching from organic N sources, at least in the short term. The main reasons for lower crop availability of N in organic amendments, compared with mineral fertilizers, are that some N is bound in organic compounds and not directly accessible to the crop (Gutser et al., 2005) and that easily degradable organic carbon feeds soil microorganisms, which need N for their growth, that is N is immobilized (Sørensen & Jensen, 1995). With repeated addition of organic amendments, soil reaches higher N mineralization capacity (Persson & Kirchmann, 1994). Mineralized N can be used by crops in later years, but if it becomes available off-season it may contribute to greater leaching (Bergström & Kirchmann, 1999). Crop uptake of N from organic sources can also be lower for reasons such as poor timing of N supply in relation to crop demand (Goulding et al., 2000). Organic amendments are often voluminous, which means they must be applied when soil conditions allow heavy traffic. They may also be sticky and heterogeneous, which complicates distribution and dose control. This may lead to lower N recovery and increased leaching in the short term (Pang & Letey, 2000). Poor synchronization between N supply and crop demand can also result from N release being too slow to match the period of crop uptake, which is often very short. Release of N could theoretically be improved by anaerobic digestion of slurry, which breaks down some of the organic N to organic acids and ammonium (NH_4^+). This, in turn, would provide some potential to reduce N leaching. However, in a review on the effects of anaerobic digestion of organic amendments, Möller (2015) found no differences between digested and untreated feedstocks on field-level N leaching.

Different methods have been used for estimation of N leaching from arable land. Some of these methods include measurements of drainage water flow and flow-proportional sampling, whereas other methods are limited to temporal sampling of soil water without considering the drainage volume at the time. The use of suction cups is an example of the latter (Webster et al., 1993). A critical disadvantage of that method is uncertainty regarding how well the sampled soil solution represents the percolating soil water.

Another common approach is to use lysimeters, where all percolating water can be collected and sampled at the bottom for measuring nutrient concentrations and drainage volume (Webster et al., 1993). Lysimeters can be of variable size in terms of depth and surface area. Some lysimeters contain repacked soil, which is a feasible approach for lighter soils with low clay content. Other lysimeters are intact soil monoliths, an approach which is preferable if the aim is to draw conclusions valid for field conditions (Cassel et al., 1974). Lysimeters are usually too small for normal farm operations and must be managed by hand. They provide a closed system with a high degree of control. However, because of the small size of lysimeters, any crop damage or irregularities in the soil may cause large experimental errors and potential edge effects are over-represented.

Leaching can also be estimated from separately tile-drained plots, where the water flow in the drains and the nutrient concentration of the drainage water are measured. However, in order to calculate total nutrient leaching, assumptions are needed regarding the proportion of water flow that bypasses the drains and percolates towards deeper subsoil (Bergström, 1987). Furthermore, groundwater may enter the drains and it may be difficult to know the exact area drained by each tile drain.

A few studies have assessed different methods for measuring N leaching. Wang et al. (2012) and Webster et al. (1993) compared the use of suction cups and monolith lysimeters and concluded that both may be used for measurements on unstructured soils. However, for soils with a potential for preferential flow, suction cups did not provide useful results, as samples did not seem to be representative of the drainage water in the soil profile (Wang et al., 2012). Bergström (1987) compared leaching estimates from one tile-drained field and three different types of lysimeters for a stratified soil with clay loam topsoil (0–27 cm) and sand (27–54 cm) overlying clay. In each of the facilities, different crops and/or N rates were tested. The results revealed substantial discrepancies between the different methods in leached amounts of N, but the different methods mostly gave similar rankings of the treatments with respect to leached amounts of N. Bergström (1987) concluded that all methods tested were suitable for studies comparing the relative effects of contrasting treatments.

Nitrogen leaching related to different fertilizer strategies was much studied 20–40 years ago. However, since crop productivity has continued to increase and techniques for management and spreading of animal manures have evolved, fresh efforts are needed in this area of science. The present work also contributes to the few studies which compare leaching measurement methods. Specific objectives of the work were to compare:

a. leaching of N from five fertilizer treatments over three years, including different fertilizer N rates and N sources and

b. measured drainage discharge, N concentration and N leaching from a tile-drained field and from lysimeters for three of the treatments over 16 months.

The leaching measurements were performed as part of a larger field study at Lanna research station in 2014–2016, where the fate of N in five different fertilizer treatments was studied.

2 | MATERIAL AND METHODS

2.1 | Site

The study was conducted at Lanna research station (58°20′N, 13°7′E, 80 m a.s.l.), which is located on an agricultural plain in southwestern Sweden dominated by grain cropping. The soil at the site is a silty clay, with 40%–46% clay and 2.3%–3.5% organic matter in the topsoil. It is classified as a Cambisol (Greve et al., 2000). Long-term (1961–1990) mean annual air temperature at the site is 6.1°C, and mean annual precipitation is 558 mm. Annual precipitation during the three agronomic years studied (1 April 2014 to 31 March 2017) was 640, 548 and 399 mm, respectively (for monthly distribution, see Figure 1). Atmospheric deposition of N in the area was estimated to be 6 kg N ha^{-1} yr^{-1}.

2.2 | Fertilizer treatments and crops

The crops grown in both field and lysimeters were winter wheat (2014) and spring barley (2015). In the field, spring oats were grown in 2016. The N doses were larger in 2014 than in 2015 and 2016, since winter wheat needs more N input to reach optimum yield than barley and oats (Table 1). Starting in 2014, there were five fertilizer N treatments, including a control, in both field and the lysimeters:

- Control (no N added) (C)
- Normal mineral N application (NM)
- High mineral N application (HM)
- Biogas digestate (BD)
- Pig slurry (PS)

All treatments, including the control, received the same amount of phosphorus (P) and potassium (K) fertilizer. The NM treatment represented fertilizer application with mineral N rates applied according to the recommendations by the Swedish Board of Agriculture 2014–2016. It matched the expected economic optimum for winter wheat in 2014, barley production in 2015 and oats in 2016. The HM treatment involved 50% higher mineral fertilizer N input than in the NM treatment.

In the lysimeters, a second application of mineral fertilizer was unfortunately not provided in the NM and HM treatments in 2014, halving the total N application in these treatments compared with the field. Thus, the comparison between lysimeters and the tile-drained field was limited to the C, BD and PS treatments. The application of 10 kg N ha^{-1} in the C treatment in the lysimeters in 2015 (Table 1) was for a parallel ^{15}N experiment in the lysimeter facility (it was actually 11 kg ^{15}N, but the same number of atoms as in 10 kg N with the N-isotope ratio of N in air).

The pig slurry used originated from fattening pigs. The raw material for the biogas digestate was also mainly slurry from fattening pigs, although not from the same farm as in the PS treatment. During field application, samples of pig slurry and biogas digestate were taken for chemical analysis. The large amount of pig slurry applied in 2014, combined with high concentration of total N, led to a very large supply of N that year (Table 1). Ammonium (NH_4^+) concentrations were similar in the two amendments in 2014 and 2015, but higher for the untreated slurry in 2016.

2.3 | Tile-drained field

The field experiment had 20 plots, each 20 m × 21 m and each with a separate tile drainage system (Figure 2). The drainage system was installed in 2008. Distance between the pipes was 7 m, and drainage depth was 1.0–1.4 m. The drainage pipes were placed on a bed of gravel in each trench

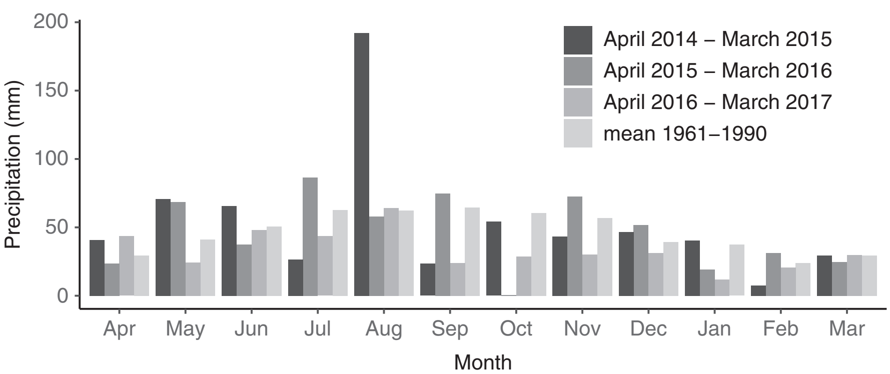

FIGURE 1 Monthly precipitation for the agronomic years (April-March) 2014, 2015 and 2016 and mean precipitation during the reference period 1961–1990

TABLE 1 Fertilizer treatments in the field 2014–2016 and in the lysimeters 2014–2015 (removed in autumn 2015). For organic amendments, plant-available nitrogen (N) was represented by the NH_4-N content, while for mineral fertilizers all N was plant-available (NH_4-N + NO_3-N). Treatments: BD, biogas digestate; C, control; HM, high mineral N; NM, normal mineral N; PS, pig slurry. Other abbreviations: pl. avail., plant available; tot, total

		Mineral fertilizer (kg N ha^{-1})		Organic fertilizer (kg pl. avail. N (tot N ha^{-1}))		Total fertilizer (kg pl. avail. N (tot N ha^{-1}))	
Year	Treatment	Field	Lysimeters	Field	Lysimeters	Field	Lysimeters
2014	C	0	0	0	0	0	0
	NM	160	80	0	0	160	80
	HM	240	120	0	0	240	120
	BD	80	80	91 (122)	91 (122)	171 (202)	172 (201)
	PS	80	80	160 (238)	167 (247)	240 (318)	247 (327)
2015	C	0	10	0	0	0	10
	NM	120	115	0	0	120	115
	HM	180	172	0	0	180	172
	BD	55	55	108 (127)	94 (109)	163 (182)	149 (164)
	PS	55	55	70 (86)	65 (77)	125 (141)	120 (132)
2016	C	0	–	0	–	0	–
	NM	120	–	0	–	120	–
	HM	180	–	0	–	180	–
	BD	55	–	70 (92)	–	125 (147)	–
	PS	55	–	86 (112)	–	141 (167)	–

according to standard practice. Each plot was surrounded by vertical plastic sheets beneath ploughing depth to prevent lateral water movement across plot borders. We assumed that there were no lateral water movement and no water bypassing the drains. Fertilizer treatments in these plots were arranged in a randomized block design, with four replicates per treatment (Figure 2).

Drainage water discharge was measured automatically every 0.75 L (corresponding to 0.0018 mm water for the plot area) with a wagging vessel for each plot. After every 7.5 L, subsamples of 15 ml were collected by a peristaltic pump into individual polyethylene bottles for each plot. These bottles were sampled for N content every two weeks during periods when drainage water was available.

2.4 | Lysimeters

The soil monoliths for the lysimeter experiment were collected in late June 2013, when the soil was dry. They were extracted in the field surrounding the tile-drained plots, which means that they had the same content of clay and organic matter and the same history of fertilizer application as the field. A drilling technique described by Persson and Bergström (1991) was used, resulting in undisturbed monoliths. The lysimeter containers had an inner diameter of 0.295 m and length 1.180 m and were made of polyvinyl chloride (PVC). Fifteen 0.800 m long and 0.295 m wide soil columns were inserted into these containers. They were stored in a barn until installation in the ground at the lysimeter facility in August 2013, after which the drain outlet was connected to an underground sampling station. At the bottom of each lysimeter, there was a filter, underneath which was a layer of coarse filler (particle size 2.0–3.5 mm), which made the lysimeter drainage system resemble the arrangement in the field. The experimental treatments were assigned to the 15 lysimeters and arranged in a randomized block design, with three replicates per treatment. Grass was sown between the lysimeters in 2014, in order to reduce the weather exposure of the crop.

The drainage water was sampled every two weeks when there was enough drainage water, to determine the N concentration. At times with very large amounts of drainage water, sampling was done weekly, to avoid overflow in the water collection containers. For the measuring of drainage discharge, scales with continuous logging every 15 minutes were installed.

The monoliths for the lysimeters were stored in darkness from June to August 2013. During storage, the lysimeter crop died, leaving unused mineral N in the soil profile. In order to reduce the impact of this remaining N pool and account only for the effects of the fertilizer treatments starting in 2014, results presented in this paper are limited to the period from 20 May 2014 to 16 September 2015. During this period, N concentrations were measured on a total of 17 occasions.

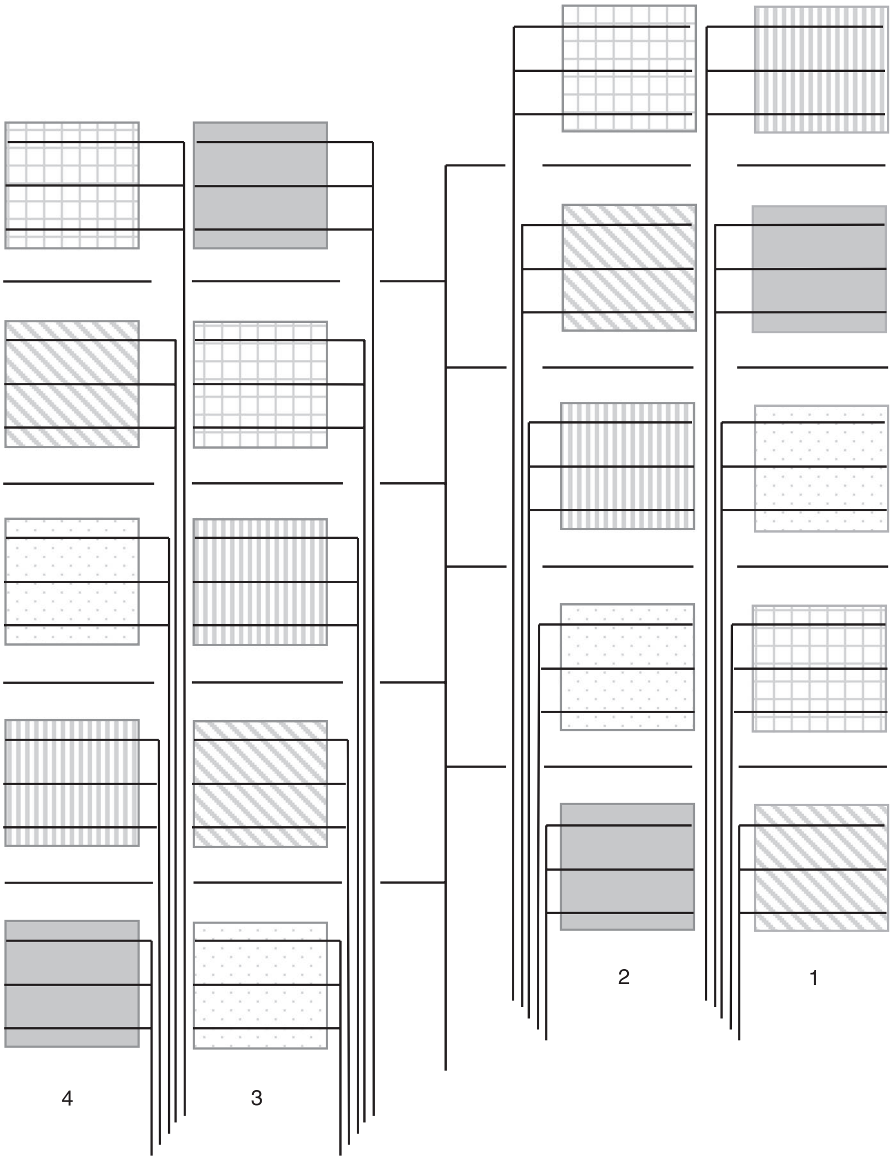

FIGURE 2 Principal layout of the tile-drained field. The black lines represent the drainage tiles. Each plot is drained separately. Numbers indicate the blocks. Treatments: dotted plots = control, checked plots = normal mineral N, filled plots = high mineral N, vertically striped plots = biogas digestate and plots with slanted stripes = pig slurry. Each plot measures 20 m * 21 m. Note that proportions are not exact

Lysimeters were uninstalled and brought to the laboratory on 16 September 2015.

Drilling for lysimeter extraction was done when the soil was dry, to avoid further shrinkage after uptake. However, on some occasions, a small gap of 3–5 mm was observed between the soil and the lysimeter wall in the top 3 cm. In those cases, soil was gently pushed to the edges by hand to fill the gap.

2.5 | Analysis of N concentration

The analysis procedure for N concentrations was the same for drainage samples from the field and from the lysimeters. Both nitrate (NO_3^-)/nitrite (NO_2^-) and total N concentrations were determined. Total N was chosen for presentation of the results of this study. The two measurements were in most cases similar, indicating that nitrate/nitrite was the dominant N form in the drainage water. Total N concentrations were determined using the combustion method, according to the European standard (SS-EN 12260:2004). The instrument used was TOC-VCPH, including TNM-1 and ASI-V (Shimadzu). The sum of N in NO_3^- and NO_2^- was determined by the photometric method according to the standard SS-EN ISO 15293-1:2013, and the instrument used was a Gallery Discrete Analyzer (Thermo Fisher Scientific).

2.6 | Operations in the field and in lysimeters

Ploughing and harrowing were performed with machines in the field, but manually in the lysimeters. Weed control was done by herbicide application in the field and hand weeding in lysimeters. Field operations in both facilities were conducted within the same week, except for ploughing after winter wheat, which was done in late October in the field and in March or April in the lysimeters. Only small amounts of barley straw were incorporated in the soil at ploughing.

2.7 | Measuring crop yields and N offtake

In the tile-drained field, three areas per plot, each 20 m^2, were harvested separately, and a sample from each area was sent for analysis. Grain samples were weighed, dried at 60°C and weighed again, after which litter was removed and weighed. Contents of water and N in dried samples were determined using near infrared transmission (NIT) spectroscopy. Nitrogen offtake (N in yield) was determined from the yield per hectare and the N content of that yield. Yield per hectare was calculated from the cleared grain samples, adjusted to 86% dry matter (DM).

2.8 | Gap filling

For the tile-drained field, 826 measurements of N concentration were performed between 1 April 2014 and 31 March 2017 in the five treatments, and eight values were missing because of technical problems. Gap filling was performed to keep all four replicates per treatment throughout the three years of measurements. In each case of missing values, the N concentration (c, as mg L^{-1}) was calculated based on a combination of measurements from other plots of the same treatment in the same period, and one existing value from the same plot in a neighbouring period. Below is an example of how this was calculated for one missing concentration in plot 2 of treatment PS during period i ($c_{i,PS2}$):

$$c_{i,\,PS2} = \frac{1}{3} \times \left(\frac{c_{i,\,PS1}}{c_{i-1,\,PS1}} + \frac{c_{i,\,PS3}}{c_{i-1,\,PS3}} + \frac{c_{i,\,PS4}}{c_{i-1,\,PS4}} \right) \times c_{i-1,\,PS2}$$

where $c_{i,PS1}$, $c_{i,PS3}$ and $c_{i,PS4}$ are the N concentrations measured in plots 1, 3 and 4 of the PS treatment, respectively, in period i, and i-1 indicates the period preceding period i.

In the lysimeter measurements, there were no missing values.

2.9 | Calculations

Most calculations are described in the text when first mentioned. To avoid repetition, calculations which were similar for the field and the lysimeters are presented here. Nitrogen leaching (leach), as kg total N ha^{-1}, was calculated for each period i of N concentration measurements as:

$$\text{leach}_i = dd_i * c_i * 0.01$$

where dd_i is the sum of drainage discharge (mm) during period i and c_i is the concentration of total N (mg L^{-1}) during the same period i. Mean N concentration over longer periods (e.g. involving N concentration periods 1 to n, $\bar{c}_{1\rightarrow n}$) was calculated from total leaching and total drainage discharge during that whole period:

$$\bar{c}_{1\rightarrow n} = \frac{\sum_{i=1}^{n} \text{leach}_i}{\sum_{i=1}^{n} dd_i * 0.01}.$$

2.10 | Statistics

A linear mixed-effects model was used to describe cumulative N leaching from the tile-drained field per agronomic year, with treatment, block and year as fixed effects and plot as a random effect. Differences between treatments were tested by pair-wise comparisons for each year. For all possible treatment pairs, the difference in annual mean leaching (where the means were estimated marginal means) was calculated, as well as p-values for these comparisons. Because of the small number of replicates ($n = 4$), no adjustment for multiple comparisons was made. All statistical tests were performed at 5% significance level. A similar model was used in all cases where statistical analyses were made for each year of the study separately, that is for yields, N offtake, yield-scaled leaching and leaching in relation to N offtake.

For comparisons including only one cumulative value per plot/lysimeter, it was considered unnecessary to use a mixed model, and instead, analysis of variance (ANOVA) was performed on a linear model including treatment and block and then Tukey's HSD for a post hoc analysis. This was used for cumulative N leaching, cumulative drainage discharge and mean N concentration for the whole field measuring period (1 April 2014 to 31 March 2017). It was also used for the field plots and for lysimeters during the lysimeter period (20 May 2014 to 16 September 2015).

A linear regression model, based on the presumption that drainage discharge, N concentration and consequently N leaching, would be similar in the two measuring facilities at a given point or interval of time, was used to compare measurements from the field with those from lysimeters:

$$\text{model} = \text{lm}\,(\text{Lysimeters} \sim \text{Field}).$$

Means per facility and treatment were used. To avoid effects of potential differences in water run-through speed in the two facilities, drainage discharge data were aggregated per month before comparison. For N concentrations, the comparison was based on synchronized periods of measurements, meaning that when measuring intervals were shorter for one of the facilities, periods were aggregated to match the intervals of the other facility. Discrepancies of up to 6 days in start/end date of a measuring interval between the two facilities were accepted without compensating actions. Leaching of N was compared using cumulative data per month. Graphical comparisons were made, where lysimeter data were plotted against field data, including a regression line and confidence band (95%). The coefficient of determination (r^2) was also calculated and used in the comparison of lysimeter and field outcomes.

Standard deviation (SD) was used to describe the variability of measurements. For drainage discharge, SD was calculated as:

$$\mathrm{SD} = \sqrt{\frac{\sum_{i=1}^{n}(dd_i - \overline{dd})^2}{n-1}}$$

where dd_i is the drainage discharge of plot/lysimeter i, $\overline{dd}$ is the mean drainage discharge in all plots/lysimeters and n is the number of plots/lysimeters. Standard deviation of N concentrations was calculated similarly.

The programming software R (R Core Team, 2019) was used for calculations, plotting and statistics, with the addition of the packages *tidyverse* (Wickham et al., 2019), *emmeans* (Lenth et al., 2019) and *lubridate* (Grolemund & Wickham, 2011).

3 | RESULTS

3.1 | Yields and N offtake

In the field, yield and N offtake were in most cases similar for the NM, BD and PS treatments. For these three treatments, yield 2014–2016 was 6100–7700 kg (86% dry matter) and N offtake was 76–136 kg N ha^{-1} year^{-1}. The HM treatment had 300–900 kg higher yields than the other fertilized treatments, and in most cases, these differences were significant. The HM treatment also had 20–60 kg N ha^{-1} higher N offtake than the other fertilized treatments, and this difference was significant for all years. The yield in the control was 2500–3500 kg ha^{-1} year^{-1}, and the N offtake was 28–43 kg N ha^{-1} year^{-1}. For both variables, this was significantly lower than in all other treatments during all three years ($p < 0.05$).

In 2014, hares, moles and birds ate most of the wheat crop in the lysimeters at late stages of crop development, and no yield was measured in the lysimeters in that year. In 2015, yield and N offtake in the PS lysimeters were of roughly the same magnitude as in the field, except for one lysimeter in block 3, which was eaten by animals just before harvest. In the C treatment, yields and N offtake were higher in the lysimeters (which had some ^{15}N input; Table 1), while for the BD treatment both yield and N offtake were considerably lower in the lysimeters compared with the field.

3.2 | Nitrogen leaching from field plots

3.2.1 | Comparison of fertilizer treatments

The HM treatment had higher total N leaching per hectare than the control in 2014–2015, but not in 2016. There were also either significant differences or tendencies for more leaching from the HM treatment compared with the NM, BD and PS treatments in 2014–2015 (Figure 3a). The control had significantly more yield-scaled leaching and leaching in relation to N offtake than the other treatments (Figure 3b,c). All treatments showed the same leaching pattern over time, although with differences in amplitude (Figure 4). In the first two years, 80%–85% of leaching happened between 1 September and 31 March, that is when there was no crop. For the agronomic year 2016, this figure was approximately 60%.

Most of the observed treatment differences in leaching per unit area originated from differences in N concentrations in the drainage water. The HM treatment had significantly higher N concentrations in drainage water, as an average for the whole three-year period, than the other treatments (Table 2). For the same time period, the mean N concentration in the NM treatment was significantly higher than in the control. There were no significant differences in N concentrations of the BD and PS treatments compared with the C or NM treatments. No significant differences were observed in drainage discharge between treatments, although higher drainage discharge from the control treatment was temporarily observed in late summer in both facilities in both years.

3.2.2 | Other factors influencing N leaching

There were large differences in N leaching between years. Numerically, differences in mean leaching per hectare were larger between years than between treatments (no statistical analysis made) (Figure 3a). During the three years of measurements, there were some clear differences between blocks, particularly in drainage discharge (data not shown). Block four had more drainage discharge than the other blocks (p = 0.005–0.01), but there was also large variability within blocks. To check the potential influence of differences between blocks on the comparison of treatments, we calculated N leaching with mean drainage discharge of all plots for each treatment. There were only minimal differences in the statistical results (Table 2).

We expected drainage water volumes to depend on yield from each plot, as transpiration is higher from a lush and leafy crop than from a sparse crop. In the first two years, we saw such a tendency when drainage discharge per unit yield in the

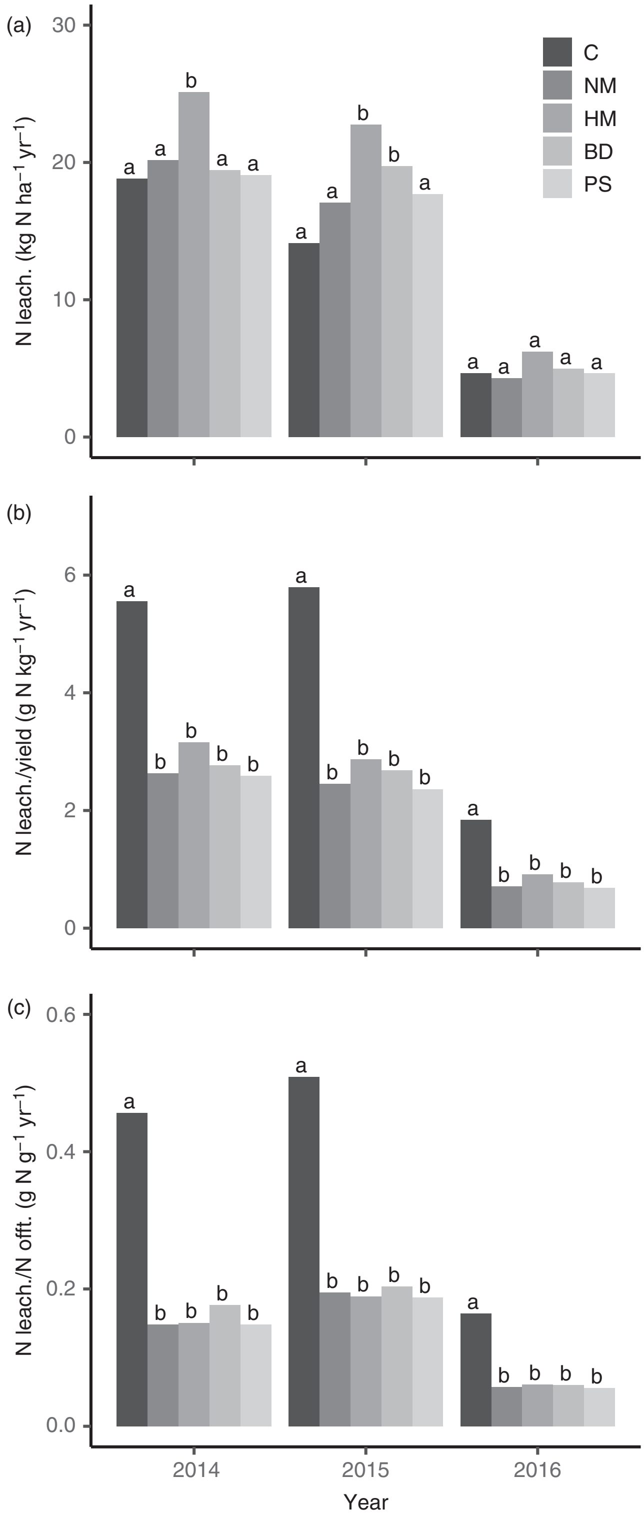

FIGURE 3 Nitrogen leaching per treatment and agronomic year (April-March), (a) per hectare, (b) per kg yield and (c) per g N in yield, measured in the tile-drained field, as treatment means. Results of statistical comparisons are given as compact letter display above the bars, where presence of the same letter within the same year indicates no significant difference ($\alpha = 0.05$). Comparisons were only made within, not between, years. Treatments: BD, biogas digestate; C, control; HM, high mineral N; NM, normal mineral N; PS, pig slurry. Other abbreviations: leach., leaching and offt., offtake

control plots was compared with that in the fertilized plots ($p = .10$–$.27$). However, when comparing drainage discharge per unit yield among fertilized plots only, no such tendency was observed.

3.3 | Comparison of lysimeters and the tile-drained field

Monthly drainage discharge followed the same pattern in both facilities and in most cases was of similar magnitude, although the discharge was generally somewhat higher in the field (Figure 5). The relationship was described by a linear function ($r^2 = .74$) (Figure 6a, b). One month during the period of measurements, namely August 2014, which had extremely high precipitation, produced outliers in all treatments (Figure 1 and Figure 6a,b). This gave very high drainage discharge in all treatments of the lysimeters, but a more moderate response in the field, particularly in the fertilized treatments (Figure 7). For N concentrations, the relationship between the measurements from the two facilities was not as clear, and a linear function did not fit the data closely ($r^2 = .56$) (Figure 6c,d). However, in both the field and the lysimeters, N concentrations in all treatments peaked in May 2015 (Figure 8). For the rest of the measuring period, concentrations stayed below 10 mg L^{-1} in both facilities.

Cumulative drainage discharge May 2014–September 2015 was slightly lower in the lysimeters than in the field. Together with slightly lower mean N concentrations in lysimeters than in the field over the same period, this gave slightly lower N leaching from lysimeters than from the field. None of these differences was significant, or even close to significant (Table 3). Still, lower leaching in the lysimeters compared to the field was also reflected in the regression line describing the relation between leaching measured in lysimeters and in the field (coefficient of $x = 0.64$; $r^2 = 0.70$).

The differences between treatments in leached amounts of N were similar in both facilities. In both cases, mean cumulative N leaching May 2014–September 2015 in the control was 1–2 kg N less per hectare than in the BD and PS treatments, which was a consequence of lower N concentrations in the control in both facilities (Table 3 and Figure 8). However, variability between replicates was large in both facilities, and none of the differences between the C, BD and PS treatments was significant (field leaching: $p = 0.60$–0.94; lysimeter leaching: $p = 0.94$–1.00). For drainage discharge, variability across all plots/lysimeters was greater for the field measurements (SD = 69 for the field, SD = 26 for lysimeters), while for N concentration it was greater across lysimeters, although the difference was smaller (SD = 1.5 for the field, SD = 2.6 for lysimeters).

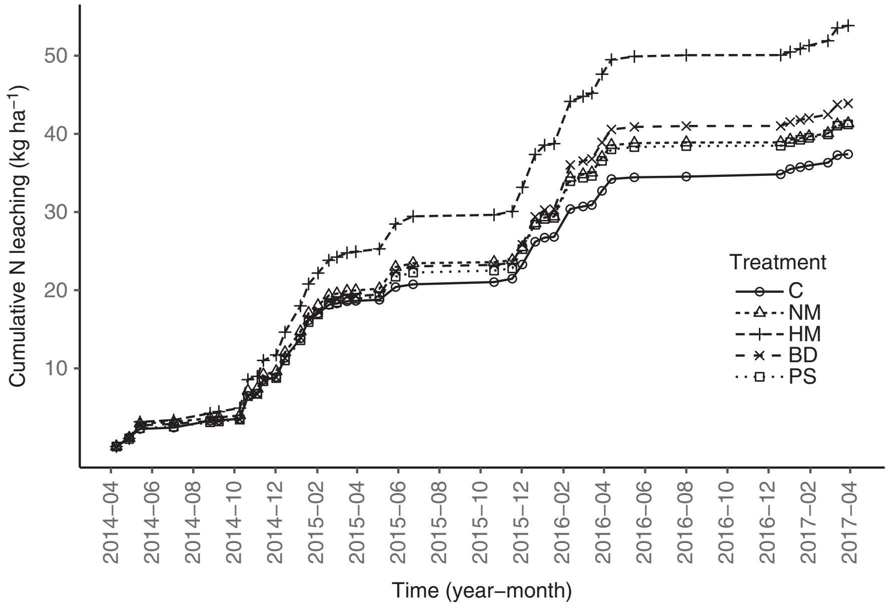

FIGURE 4 Cumulative nitrogen (N) leaching in the tile-drained field from April 2014 to March 2017, as treatment means. Treatments: BD, biogas digestate; C, control; HM, high mineral N; NM, normal mineral N; PS, pig slurry

4 | DISCUSSION

4.1 | Fertilizer treatments

Long-term studies of the impact of organic amendments on N leaching have found higher leaching from use of organic amendments compared with mineral fertilizers with similar plant-available N content (Goulding et al., 2000). In the present study, N leaching per unit area from the BD and PS treatments was at the same level as from the NM treatment in all years except 2015, when the BD treatment had higher leaching, probably as a result of higher plant-available N input compared with the NM treatment (Table 1). In the PS treatment in 2014, plant-available N input was of the same magnitude as in the HM treatment, but N leaching was still on the same level as for the NM treatment, despite high precipitation that year. Reasons for this could be that a large amount of available N was immobilized as a result of the very high C content of the slurry, and/or that there were large N losses by denitrification. There are several possible explanations for this discrepancy in the results compared with Goulding et al. (2000). First, the different results may be because of the short period of application of organic amendments in our case. Before the study started in 2014, all plots were treated in the same way for many years, exclusively with mineral fertilizers. Roots, stubble and return of straw were the only inputs of organic matter. This means that at the start of the experiment, the pool of organic matter in the BD and PS plots was not larger than in the NM and HM plots. Three years of application of organic amendments seemed to be too short in this case to give large off-season mineralization of organic N. Second, precipitation was sparse during the third year of our field study. This led to very low leaching in all treatments, so treatment effects could not be distinguished in that year (Figure 3a). Third, the organic amendment used in the study by Goulding et al. (2000) was solid manure applied in the autumn, while in our study untreated and digested pig slurry was applied in the spring. In a previous one-year lysimeter leaching study, spring application of livestock slurry was found to reduce leaching compared with application in the autumn (Bertilsson, 1988). In the same study, N uptake by the crop was greater from slurry compared with solid manure including a similar content of ammonium N, both applied in the spring. We believe that the differences in manure type and timing of application are the main explanations for the differences between our results and those presented by Goulding et al., (2000).

The HM treatment had slightly greater leaching per unit area than the NM, BD and PS treatments, and this difference was significant ($p < 0.05$) for all three comparisons in 2014 (Figure 3a). In 2015, HM had significantly greater leaching than NM and PS per unit area (Figure 3b). In both 2015 and 2016, the economic optimum occurred at a considerably higher N fertilizer rate than expected, at N levels between NM and HM treatments. Results from this and previous leaching studies show that, while excessive N input may increase N leaching, there is little to gain by reducing N input below the economic optimum (Bergström & Brink, 1986; Constantin et al., 2010; Delin & Stenberg, 2014; Meissner et al., 1995). In our study, leaching per hectare was only slightly and non-significantly higher in NM compared with the control, while the yield-scaled leaching was nearly threefold higher in the control compared with NM (Figure 3a,b). In order to reduce leaching below the level of the NM treatment, measures other than reducing N inputs below the optimum would be needed, for example growing catch crops (Constantin et al., 2010).

Similar to Bergström and Brink (1986), Constantin et al. (2010) and Goulding et al. (2000), we observed large

TABLE 2 Cumulative nitrogen (N) leaching, cumulative drainage discharge and mean N concentration per field treatment from 1 April 2014 to 31 March 2017. Drainage discharge is given both as mean per treatment and as mean of all field plots, all treatments. Leaching is calculated for both alternative drainage discharge calculations per treatment. Results of statistical comparisons are given as compact letter display, where presence of the same letter indicates no significant difference (α = 0.05). Treatments: BD, biogas digestate; C, control; HM, high mineral N; NM, normal mineral N; PS, pig slurry. Other abbreviations: conc., concentration; mean dis., mean discharge of all treatments; spec. dis., specific discharge per treatment; tot, total

	Leaching, kg tot N ha^{-1}		Drainage discharge, mm		
Treatment	Spec. dis.	Mean dis.	Spec. dis.	Mean dis.	N conc., mg tot N L^{-1}
C	38^{a}	36^{a}	754^{a}	690	5.1^{a}
NM	42^{ab}	45^{ab}	628^{a}	690	6.6^{b}
HM	54^{b}	56^{b}	658^{a}	690	8.2^{c}
BD	44^{ab}	43^{ab}	720^{a}	690	6.3^{ab}
PS	41^{ab}	41^{a}	689^{a}	690	6.0^{ab}

differences in leaching between years, mainly as a result of differences in precipitation. Of the years included in this study, the distribution of precipitation in 2015 most resembled the long-term average for 1961–1990 (Figure 1). The low leaching from April 2016 to March 2017 was probably mostly an effect of low precipitation, although uptake of N and water by the winter wheat sown in autumn 2016 may also have contributed.

4.2 | Measuring facilities

4.2.1 | Drainage discharge

There are difficulties in correctly measuring drainage discharge in the field. Bergström (1987) found larger drainage volumes from lysimeters compared with a tile-drained field, but in our study mean drainage discharge per treatment was mostly similar in volume in the two facilities, or larger in the tile-drained field (Figure 5). This difference between the studies was probably primarily due to differences in soil type and drainage depth of the lysimeters. Our lysimeters had the same dimensions as those called 'small lysimeters' in the study by Bergström (1987), but while our lysimeters had undisturbed clay soil down to 80 cm depth and then fillers for drainage, the undisturbed section of the Bergström lysimeters was only 53–59 cm, where the top half was clay and the underlying layer was sand. Underneath these layers were fillers of sand and gravel. This means that surplus water was readily drained off in the Bergström lysimeters, while ours could store more water, similar to the field situation in our study. Differences in soil texture in the field may also have contributed to the differences between this study and that by Bergström (1987). The soil profile studied by Bergström had a sand layer underneath clay topsoil, which gave a greater potential for lateral water flow than the clay profile in our study.

In the linear regression of monthly drainage discharge in the lysimeters compared with the field, there were three outliers (Figure 6a,b). These represented each of the treatments in August 2014, when drainage discharge was around 40 mm greater from lysimeters than from the tile-drained field in all three treatments. That month had extremely high precipitation, 192 mm, and a large proportion of this (76 mm) fell on 19 August, that is after harvest in both facilities. The difference in response to that precipitation peak between the lysimeters and the tile-drained field represented most of the difference in cumulative drainage discharge recorded for the month of August 2014 (Figure 7). The C treatment in both facilities showed a faster and greater response to the precipitation peak than the fertilized treatments. Later ripening of the crop in the fertilized treatments than in the unfertilized control, which is usually the case, could explain the higher drainage discharge in the control. Later ripening means prolonged transpiration, which leaves more empty pore space to hold rainwater and thus smaller drainage discharge volumes. It is possible that the greater drainage discharge from the lysimeter facility had similar causes. The crop in the lysimeter facility was more exposed to sun and wind than that in the field, which may have caused earlier ripening, as also seen for the control in the field. This means reduced crop uptake of water, giving less free pore space to hold large precipitation volumes and therefore greater drainage runoff after heavy rainfall.

We expected the lysimeters to be drier because of greater exposure to wind and sun and this was also our visual impression of both crop and soil in the lysimeters. However, in sporadic measurements of soil moisture and soil temperature in the field and the lysimeters in 2015, we found no differences in soil conditions between the facilities.

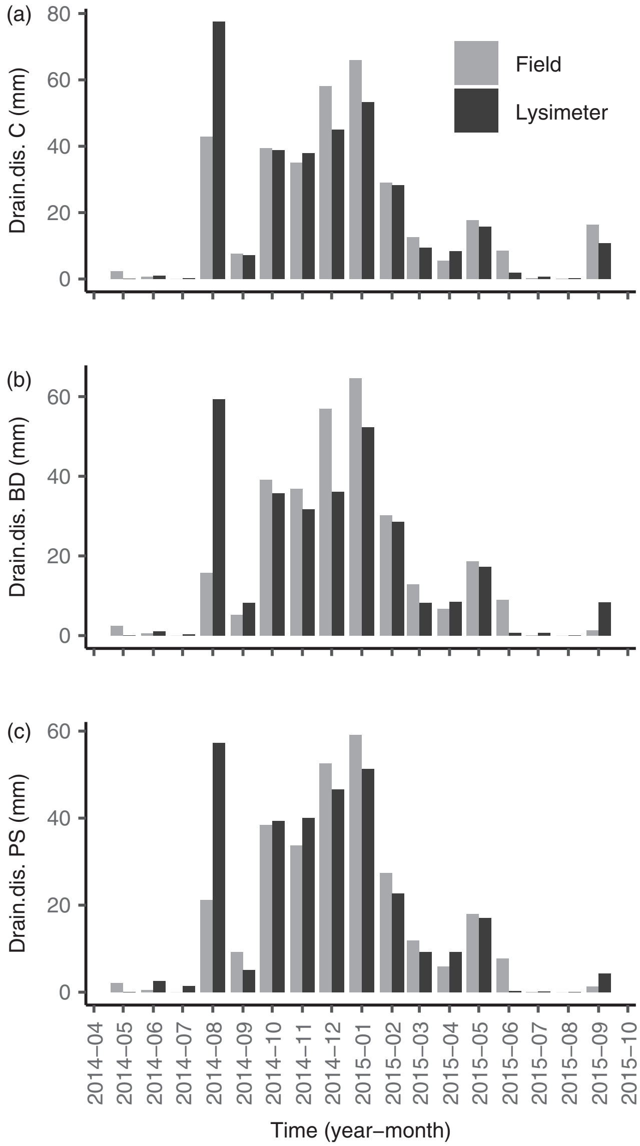

FIGURE 5 Drainage discharge (drain. dis.) per month, as treatment means, in the field and in the lysimeters, 20 May 2014–16 September 2015. (a) Control (C), (b) biogas digestate (BD) and (c) pig slurry (PS) treatments. Note different scale on the *y*-axes in (a), (b) and (c)

The variability in drainage discharge in the tile-drained field was more than twice that in the lysimeters. Some of the differences in drainage discharge stemmed from differences in yield, but this explained only a minor part of the variability. Nitrogen concentrations in drainage water did not differ much between plots of the same treatment, so we dismissed groundwater inflow as an explanation for the large drainage discharge measured in some field plots; this would have diluted the drainage water with regard to N content. This leaves lateral movement of water in the soil profile as the main possible explanation for the variability, even though such water movement is mostly not pronounced in clay soils. Despite the vertical plastic sheets installed along the field plot borders below ploughing depth, additional drainage water seemed to have entered some of the plots. As there was a distance of some metres between plots, the extra water drained from one plot should mainly have originated from this area between the plots, which had the same fertilizer regime as the treatment plot. Prevention of lateral water movement across borders is an advantage of the lysimeter approach.

While the drained volume from lysimeters can be assumed to reliably reflect precipitation less evapotranspiration and soil storage, the main advantage of the tile-drained field is that the cropping environment was similar to that in other fields in the area, that is it closely resembled commercial grain production and thus could be assumed to be representative regarding, for example, yield and N uptake.

4.2.2 | Nitrogen concentrations

In most cases, N concentrations fluctuated below 10 mg L^{-1} in drainage water both from the field and from lysimeters, and at these low levels, the correlation between the two facilities was weak (Figure 6c,d). Concentrations above 10 mg L^{-1} appeared only once and was simultaneous in both facilities (in May 2015); all treatments showed a similar pattern (Figure 8). The weak correlation at low concentrations indicates that there were factors influencing N concentration which did not work similarly in the field and in the lysimeters. The input of N fertilizers, which was similar in both facilities, seems to be just one of several important factors influencing N concentration in drainage water.

The fact that ploughing after the harvest of winter wheat was performed before winter in the field and after winter in the lysimeters (an accidental mismatch of timing in the two facilities) may have enhanced mineralization of soil N at different timepoints. This may partly explain the higher N concentrations in the leaching water from the field in early winter and from the lysimeters in spring (Figure 8). Thereby this mistake could have contributed to the weak correlation of N concentrations between the two facilities.

The particularly weak correlation in the C treatment was expected, since the absence of N fertilizer input removed the main management factor causing differences in N concentration results. The small input of ^{15}N to the C treatment in the lysimeters in 2015 (corresponding to 10 kg fertilizer N ha^{-1}) was not matched in the field, but no effect of this difference in management on N concentrations was observed (Figure 8). Measurements of N offtake instead suggested that this additional N input was taken up by the plants in the lysimeter C treatment. The general differences between lysimeter and field N concentrations in drainage water may be partly because of differences in crop

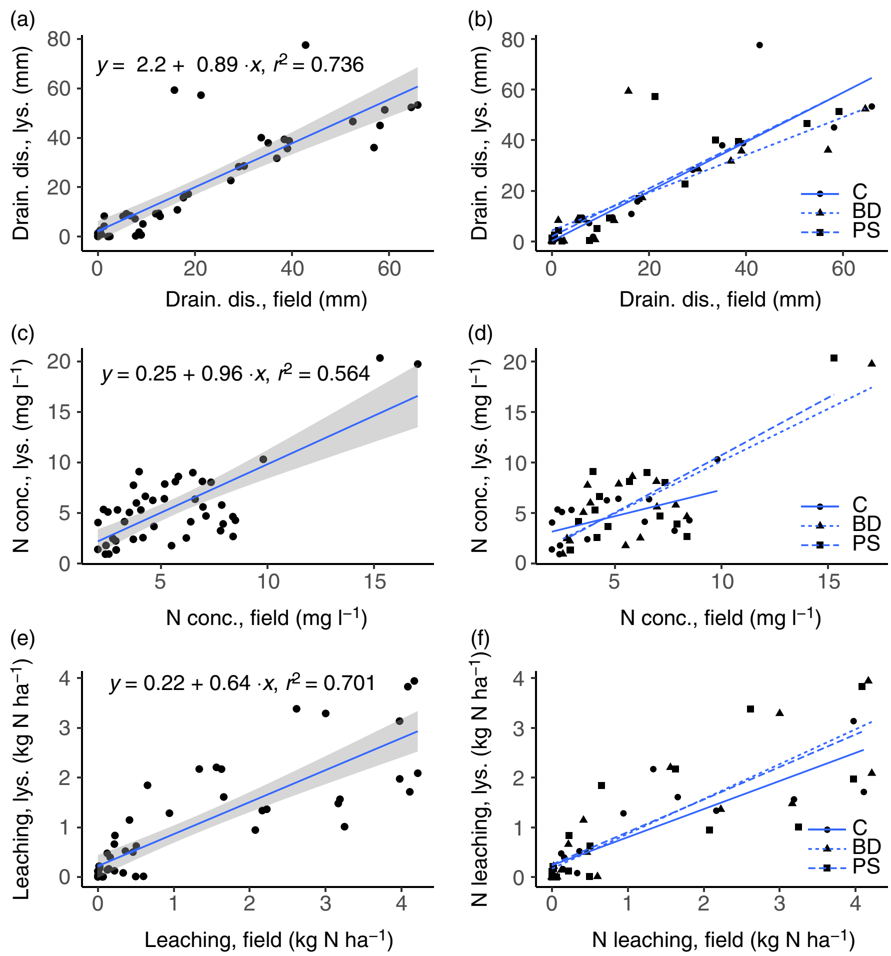

FIGURE 6 Comparison of results from field and lysimeter measurements. (a, b) Drainage discharge, (c, d) N concentration and (e, f) N leaching. The left column shows the common linear regression of all dots, including all treatments. The confidence band represents the 95% confidence level. The right column shows separate regression lines per treatment. In (a, b, e, f), each dot represents the cumulative value per month, as means per treatment. For (c, d), each dot represents the concentration value per period of N concentration measurements, adjusted to match both field and lysimeters, as means per treatment. Treatments: BD, biogas digestate; C, control; PS, pig slurry. Other abbreviations: drain. dis., drainage discharge; lys., lysimeters; conc., concentration

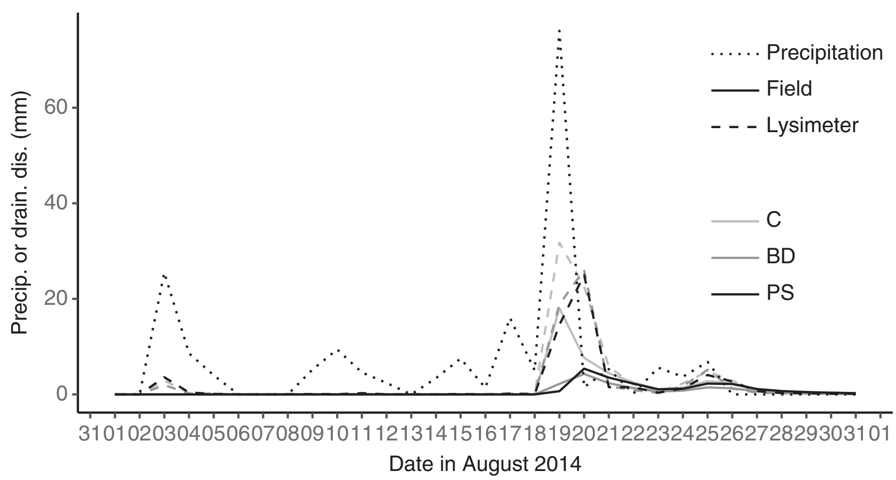

FIGURE 7 Precipitation (precip.) and drainage discharge (drain. dis.) in August 2014, for the tile-drained field and lysimeters (treatment means per day). Treatments: BD, biogas digestate; C, control; PS, pig slurry

N uptake and perhaps also drainage depth. The small differences in periodization of the N concentration measurements did not significantly contribute to the differences between facilities.

The consumption of parts of the lysimeter crop by animals in 2014 was unlikely to have influenced crop uptake of N as most of it happened at the end of the growing season (late July-early August), when the crop had already taken up practically all N it needed.

4.2.3 | Nitrogen leaching

For estimates of N leaching, N concentrations were weighted with the drainage volume to give the total losses of N per unit time and area. Despite difficulties in correctly measuring drainage discharge in the field and the weak correlation between N concentrations of the two facilities, there was a reasonably linear correlation between monthly N leaching estimates from the two facilities. Cumulative lysimeter

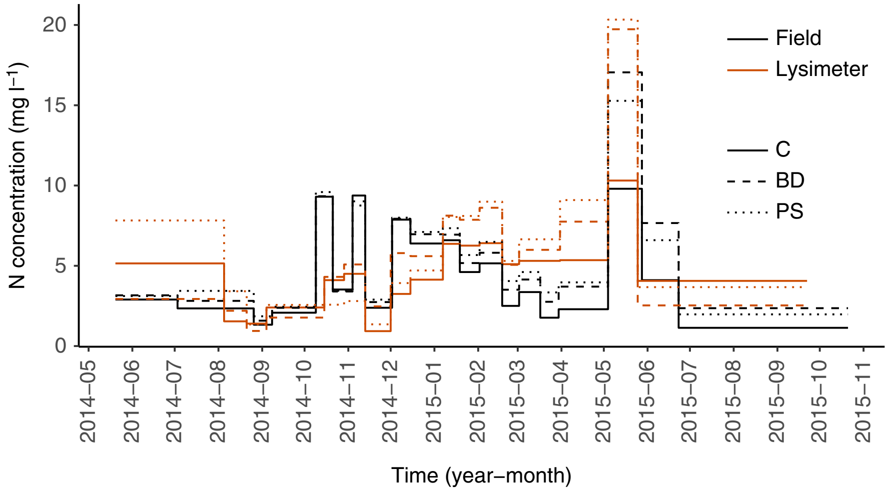

FIGURE 8 Nitrogen concentration (mean per treatment) in drainage water from lysimeters and the field, per period May 2014-September 2015. Each vertical line represents a measurement. The horizontal lines preceding each measurement illustrate that drainage water first accumulates and is then measured. Thus, the measured N concentration is valid for the whole time period since last measurement. A colour version of this figure is available in the web issue of this article. Treatments: BD, biogas digestate; C, control; PS, pig slurry

TABLE 3 Cumulative nitrogen (N) leaching, cumulative drainage discharge and mean N concentration for the control (C), biogas digestate (BD) and pig slurry (PS) treatments in the field and in the lysimeters 2014–05–20 to 2015–09–16. Values are means per treatment, with ranges presented in brackets; no significant differences between treatments or facilities were observed. Lys., lysimeters

	Leaching, total N (range), kg ha^{-1}		Drainage discharge (range), mm		N concentration, total N (range), mg L^{-1}	
Treatment	**Field**	**Lys.**	**Field**	**Lys.**	**Field**	**Lys.**
C	19 (14–22)	15 (7–29)	342 (287–431)	336 (319–362)	5.5 (4.5–7.2)	4.2 (2.0–8.0)
BD	20 (13–30)	17 (11–27)	300 (222–442)	297 (263–320)	6.9 (4.8–9.3)	5.8 (3.3–8.7)
PS	20 (14–24)	17 (12–27)	289 (240–329)	307 (301–319)	6.8 (5.1–7.4)	5.6 (3.9–8.5)

leaching for the whole measuring period was about 80% of cumulative field leaching, that is cumulative leaching was roughly of the same magnitude for both facilities (Table 3). Thereby the results from field and monolith lysimeters were more coherent than in the comparison by Bergström (1987).

4.2.4 | Recommendations

Based on experiences from this study, some recommendations can be made on measuring N leaching in tile-drained fields and in lysimeters. For tile-drained fields, we recommend checking for differences in drainage volume between plots during years with the same treatment in all plots, to map baseline differences when there are no expected systematic differences in crop transpiration, and then estimating the amount of lateral inflow of soil water from outside each plot or of drainage water bypassing the drainage pipes.

For lysimeters, we recommend (a) good protection of crops from birds, rodents and other grazing animals throughout the vegetation period, (b) establishment of surrounding vegetation that can withstand trampling and which is high enough to reduce weather exposure to levels normal for a field crop, (c) larger surface area of lysimeters (larger than our 0.07 m^2), if technically possible, in order to further reduce edge effects and variability between replicates, and (d) at least four replicates per treatment.

5 | CONCLUSIONS

In a short-term perspective, application of organic amendments does not necessarily lead to increased N leaching compared with mineral N sources, at least not in a clay soil. As this and previous studies show, application of mineral fertilizers at rates exceeding the economic optimum tends to give more N leaching per hectare than fertilizing at recommended rates.

Both lysimeters and tile-drained field plots can serve well for measurements of N leaching. Both facilities used in this study had shortcomings and can be improved, but both methods were still found to be useful with their current design.

Drainage discharge was equally well measured in lysimeters and the tile-drained field. The response in drained volumes to extreme rainfall in lysimeters and the field should be examined in future studies. Concentrations of N were within roughly the same range in both facilities. We regard these similarities as a strength of both facilities, as they suggest that measurements reasonably well reflect actual N losses through leaching.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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