

# Effects on nitrate leaching of the timing of cattle slurry application to leys

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## Abstract

This study compared the effects on nitrate leaching of slurry application to ley in early autumn (15 September), late autumn (1 November) and spring (April) under Swedish growing conditions. In two separate two-year experiments, started in autumn 2009 and 2010, on a sandy loam soil in south-west Sweden, these three application times were compared with no slurry application in grass-clover and grass swards. Soil water was sampled with ceramic suction cups, and nitrate leaching was calculated from water nitrate concentrations and drain discharge. Plant measurements indicated that, during autumn, the grass took up at least 20 kg of the 50 kg nitrogen (N) applied with slurry in September. The mineral nitrogen level in the subsoil (30–90 cm) in December was around 2 kg N ha<sup>-1</sup> higher in this treatment. Nitrate leaching was on average 5 and 6 kg N ha<sup>-1</sup> year<sup>-1</sup> higher after early and late autumn slurry application, respectively, than after spring application ( $p < .001$ ), but the difference varied from 0 to 10 kg N ha<sup>-1</sup> year<sup>-1</sup> between experiments and sward types. Nitrate leaching losses in kg N ha<sup>-1</sup> were lower from the grass sward, but higher if related to nitrogen inputs and dry matter yield. These results indicate that autumn application can increase the risk of nitrate leaching, but that early/late application within autumn is less important. It is more important to limit the amount of slurry applied in autumn and to consider other risks of nitrogen losses associated with time of application, such as ammonia emissions.

## KEYWORDS

cattle slurry, grassland, ley, manure, nitrate leaching

## 1 | INTRODUCTION

High nitrogen leaching from agricultural soil via drainage water causes eutrophication of surface waters and contamination of drinking water. High nitrate levels in soil in combination with high drainage runoff, especially from sandy soils, are associated with a high leaching risk. To minimize nitrogen leaching, nitrate levels in soil should therefore be limited during periods with high water throughflow in the

soil profile. For example, animal slurry with high levels of ammonium that is readily converted to nitrate should not be applied to soil in greater quantities than can be taken up by the crop before periods with heavy rainfall or snowmelt leading to large volumes of drainage throughflow.

The European Union Nitrate Directive (EEC, 1991) restricts manure application within nitrate-vulnerable zones. In Sweden, this means that slurry application to growing leys in autumn is not permitted after 31 October, based on the

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assumption that earlier application results in more nitrogen being taken up by the grass. However, when this restriction was implemented in Sweden in 2009, there was little scientific evidence that the risk of nitrate leaching is higher when slurry is applied in November rather than earlier in autumn. In a review of the Swedish literature, Lindén (2008) found almost no measurements of leaching effects from slurry application in autumn to ley in Sweden. The present study was conducted to fill this knowledge gap.

In Sweden, cattle slurry is usually applied to grass or grass–clover ley, since that is a common crop on cattle farms and since the nutrient content of cattle slurry is well matched to the fertilizer requirement of ley. In addition, the nitrogen in cattle slurry is probably best utilized in a crop with a long period of nitrogen uptake, since the high content of organic material in cattle slurry slows down nitrogen release (Delin et al., 2012). The standard recommendation is to apply slurry in spring, owing to reports of high ammonia ( $\text{NH}_3$ ) emissions (Huijsmans, Vermeulena, Holb, & Goedhartc, 2018) and lower crop nitrogen uptake (Hoekstra et al., 2010; Lalor et al., 2011) from summer application and elevated leaching from autumn application (Smith, Beckwith, Chalmers, & Jackson, 2002). However, farmers may prefer to apply some of their slurry in autumn, mainly for practical matters such as limited storage capacity for slurry during winter and limited time for field operations in spring under northern European climate conditions (Liu et al., 2018). The time between winter ending and grass growth in spring is limited, and application after significant grass growth is usually avoided due to fear of spores contaminating the silage (Rammer, Lingvall, & Salomon, 1997).

According to the EU Nitrate Directive, areas should be categorized as nitrate-vulnerable zones if nitrate concentrations in surface waters exceed  $50 \text{ mg L}^{-1}$  or if there is a risk of this limit being exceeded unless measures are taken. In Sweden, approximately half of southern and central Sweden, representing 75% of Swedish arable land, lies within nitrate-vulnerable zones. For farmers, this means more stringent restrictions than previously (before 2009). One restriction is the extended winter period when no slurry may be applied, which now runs from 1 November until 28 February. This period previously varied between the Swedish regions, but was 1 January to 15 February for many areas. In the southern counties of Sweden (Skåne, Blekinge and Halland), slurry must be applied by band spreading underneath plant cover, followed by soil incorporation, with dilution of slurry with water prior to application or with irrigation within four hours after application. Another restriction is that, on average per farm, no more than  $170 \text{ kg total N}$  may be applied as slurry during one year. Application of slurry with readily available nitrogen before autumn-sown crops is restricted to  $60 \text{ kg ha}^{-1}$  for winter oilseed rape and  $40 \text{ kg ha}^{-1}$  for other autumn-sown crops.

The leaching risks arising from slurry application in autumn most likely differ depending on the winter climate. In a Nordic project (Larsen, 1987), significantly lower ley yields were observed after autumn application compared with spring application in Denmark (Jutland), whereas in Finland and central Sweden (Uppland) the effects on yield were similar regardless of whether slurry was applied in autumn or spring. In trials in western Sweden, higher ley yield was obtained after autumn application than after spring application (Albertsson, 1997, 1998). When different slurry application dates in autumn were compared in experiments in southern Sweden, the average yield did not differ between treatments (Hallin & Jansson, 2002; Andersson, 2002).

Application in early autumn could be an advantage compared with application in late autumn, since in early autumn nitrogen can be assimilated by the crop and thus protected from being leached with drainage water during winter. However, the degree of uptake is limited and excess ammonium will have more time to nitrify and be transported down through the soil profile to the drainage system than ammonium applied with slurry later in autumn. In late autumn and winter, the temperature in Sweden is usually low and drainage from frozen soil is limited. Low temperature means slow nitrification (Malhi & McGill, 1982) and no drainage means no transport of nitrate. However, in large areas of Sweden, the winter can sometimes be mild and drainage can be considerable. The aim of this study was to compare the nitrate leaching effects of cattle slurry application to grass ley and grass–clover ley in early autumn, late autumn and spring under Swedish growing conditions.

## 2 | MATERIAL AND METHODS

### 2.1 | Experimental site

The experimental site was Götala in south-west Sweden ( $58^{\circ}22\text{N}$ ,  $13^{\circ}29\text{E}$ ), on a Cambisol (FAO Soil Taxonomy) sandy loam soil (14% clay, 22% silt and 64% sand) with pH ( $\text{H}_2\text{O}$ ) 6.4 and 2.8% soil organic matter (1.6% C and 0.14% N) in the 0–30 cm layer. Cation exchange capacity (CEC) of the soil is  $130 \text{ mmol}_c \text{ kg}^{-1}$  dry soil and base saturation 78%. The subsoil has a larger fraction of coarse sand in the 30–60 cm layer (12% clay, 17% silt and 71% sand) and the 60–90 cm layer (13% clay, 20% silt and 67% sand). The site was considered representative of livestock farms in south-west Sweden in terms of soil management practices (repeated manure addition over the years) and location (close to a livestock-dominated area with similar soil texture, whereas cereal-dominated areas are on plains soils with higher clay content). According to the calendar definition of seasons used in Sweden, autumn runs from 1 September to 30 November and

spring from 1 March to 31 May. According to the meteorological definition (mean daily temperature below 10°C), autumn normally starts around 20 September in the region and winter (mean daily temperature below 0°C) normally starts around 4 December and lasts until 16 March. Precipitation and temperature were recorded at the site throughout the experiment (Figure 1). Mean annual precipitation was 582, 685 and 854 mm in the years 2009/2010, 2010/2011 and 2011/2012, respectively, of which 281, 124 and 172 mm fell in the period October–February. Mean annual rainfall was higher than average in 2010/2011 and 2011/2012, but precipitation in October–February was lower than average, especially in 2010/2011. In contrast, 2009/2010 had lower than average annual precipitation, but much more than average in October–February.

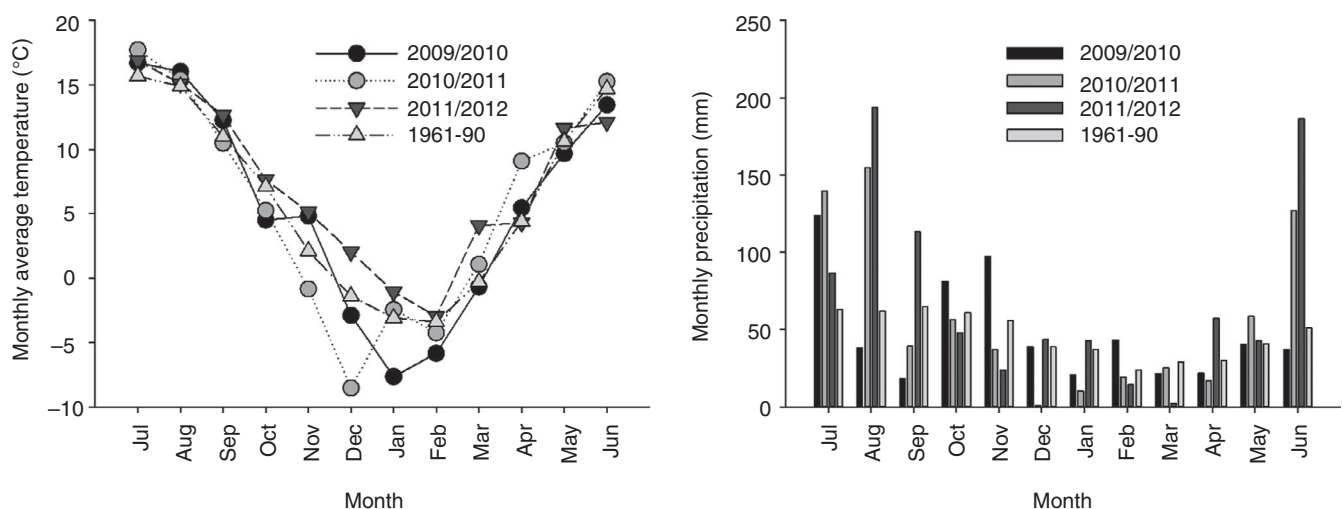
## 2.2 | Experimental layout

Field experiments were carried out in ley to compare nitrate leaching after application of cattle slurry in early autumn (September), late autumn (November) and spring (April) to first- and second-year ley. For this, one two-year ley was established in 2009 and another in 2010, with one two-year experiment in each case (2010–2011 and 2011–2012 in experiments 1 and 2, respectively). The leys were cut three times per year. Ley is normally established by under-sowing with spring cereal in the year before the first cut. Ley was under-sown with spring barley in spring 2009 in the first experiment and with winter wheat in spring 2010 in the second experiment. To avoid strong competition from the main crop, the winter wheat was only fertilized moderately and harvested in July, before ripening. Each experiment had four treatments (Table 1). With 28 plots available, these four treatments were replicated and randomized in seven blocks. Three

of these blocks had a ley comprising only the grass species timothy (*Phleum pratense*), meadow fescue (*Festuca pratensis*) and ryegrass (*Lolium perenne*). The other four blocks had a grass–clover ley, comprising the same grass species as in the grass ley, combined with 10% red (*Trifolium pratense*) and 10% white (*Trifolium repens*) clover. In order to avoid clover migration from grass–clover ley to pure grass ley, the blocks with each ley type were kept together.

## 2.3 | Fertiliser application

The cattle slurry was applied with trailing hoses, which is the common slurry application method for slurry to growing ley. Spreading width was 4 m, and plot size was 6 m wide and 30 m long, which meant that a 1-m strip on each side of the slurry-treated area was left unmanured. The treatments were repeated in the same plots during the two years. Plots with the treatment without slurry received a similar dose of nitrogen, phosphorus and potassium with mineral fertilizer in spring as the treatments with slurry (Table 1). In one treatment, slurry was applied around 15 September or after the last cut, in the next it was applied around 1 November and in the last it was applied in spring before crop growth and when soil conditions were good (Table 1). The actual dates and rates of slurry application differed slightly from the plan (Table 2), due to differences in cutting dates, differences between years when conditions were favourable for slurry application in spring and difficulties in correctly estimating the ammonium content of the slurry at the time of application. The dry matter content of the slurry was on average 5%. In addition to the slurry, all treatments received additional nitrogen and potassium with mineral fertilizer during the growing season, to meet the normal recommendations for ley in the area.



**FIGURE 1** Mean monthly temperature and precipitation at the experimental site during the study period

**TABLE 1** Experimental plan and fertiliser application level in the different treatments

Slurry application	Ammonium-N with slurry (kg NH <sub>4</sub> -N ha <sup>-1</sup> )	Nitrogen, phosphorus and potassium (N-P-K) mineral fertilizer		
		Spring	After first cut	After second cut
-	-	65-15-90	60-0-90	40-0-0
15 Sept	45	25-0-0	60-0-90	40-0-0
1 Nov	45	25-0-0	60-0-90	40-0-0
1 April	45	25-0-0	60-0-90	40-0-0

**TABLE 2** Dates of slurry application and amount of ammonium nitrogen (NH<sub>4</sub>-N), total phosphorus (P) and potassium (K) supplied by slurry in the slurry treatments in the different years of the first and second two-year leys

Experiment	Treatment	Year 1		Year 2	
		Date	Amount	Date	Amount
		Year-month-day	kg N-P-K ha <sup>-1</sup>	Year-month-day	kg N-P-K ha <sup>-1</sup>
1	15 Sept	2009-09-16	49-11-109	2010-09-24	63-28-99
1	1 Nov	2009-11-03	51-15-92	2010-10-26	54-30-90
1	1 April	2010-04-13	60-20-123	2011-04-19	86-44-131
2	15 Sept	2010-09-24	63-28-99	2011-10-03	77-28-95
2	1 Nov	2010-10-26	54-30-90	2011-11-01	63-31-77
2	1 April	2011-04-19	86-44-131	2012-03-30	45-20-77

## 2.4 | Plant nitrogen in autumn and winter

In order to estimate how much of the slurry nitrogen applied the ley could take up during autumn and winter, plant nitrogen content was compared between manured and unmanured treatments. For this, plant samples were taken in autumn, before the late slurry application, in 2009 and 2011 and in early spring in 2010. Biomass in four 0.25 m<sup>2</sup> areas was cut plot-wise at the soil surface, weighed and analysed for dry matter and nitrogen content according to the Dumas method on a LECO CNS-2000 (Leco Corp., St Joseph, MI, USA) (Kirsten & Hesselius, 1983).

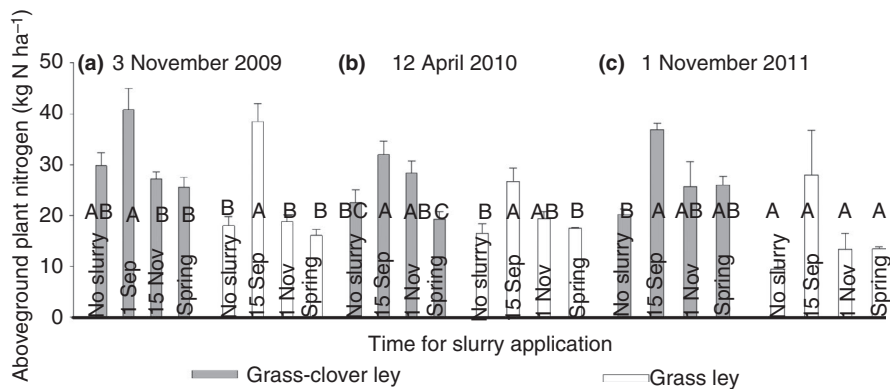
## 2.5 | Soil mineral nitrogen

In order to determine changes in soil mineral nitrogen levels and movement down the soil profile after autumn application, soil samples were taken plot-wise after the late autumn application (2 December 2009 and 21 December 2010 in experiment 1 and 15 April 2011 and 14 November 2011 in experiment 2). Composite samples of 12 subsamples from the 0–30 cm layer, and six subsamples from the 30–60 and 60–90 cm layers, were kept frozen until analysis for ammonium and nitrate concentrations. The composite samples were milled and homogenized in frozen state. Subsamples of 30 g were used for extraction with 100 mL 2 M KCl (Mulvaney, 1996). Ammonium (NH<sub>4</sub>-N) and nitrate (NO<sub>3</sub>-N)

concentrations were then analysed using colorimetric methods (Eastin, 1978) on a Technicon autoanalyser (TrAAcs800, Bran + Luebbe Analyzing Technologies Inc., Elmsford, USA) Anal. Chem.1988603183A-183A. In 2010, the trials were covered with snow during December and sampling was very time-consuming. Therefore, only the first experiment was sampled on that occasion, while the second was sampled after snowmelt in early spring 2011.

## 2.6 | Nitrate leaching

Soil water was sampled with ceramic suction cups (0655 round-bottom tapered neck cups 1 bar std 2.223x 6.985 mm, Soilmoisture Equipment Corp., Santa Barbara, CA, USA) installed in triplicate at 80 cm depth in each plot (Djurhuus & Jacobsen, 1995; Delin & Stenberg, 2014). Sampling was carried out by applying a suction of 60–70 kPa for 24 h before sampling was performed. This was done every second week during periods with drainage water runoff (i.e. periods when runoff could be measured) from the time of the earliest fertiliser application until December in the second year of cutting. Daily values of drainage flow were obtained from leaching experiments at Lanna research station (approx. 25 km from the study site), where continuous measurements of drainage runoff are made from separately drained plots with tipping bucket equipment. This means that no sampling was done during months with insignificant drainage runoff, often June



**FIGURE 2** Aboveground plant nitrogen in different treatments before late autumn application of slurry in 2009 and 2011, and before spring application in 2010

and July but sometimes also January and February if the temperature was below zero. The sampled soil solution was analysed for nitrate by flow injection analysis (Tecator AB, Höganäs, Sweden) according to the colorimetric cadmium reduction method. Nitrate–nitrogen leaching was determined from nitrate concentrations in soil water and drainage discharge. Other forms of nitrogen (particle bound) that could be expected in drainage water were not analysed, since they cannot move through the porous material into the suction cups. However, in leaching studies using other sampling methods, nitrate–nitrogen and total nitrogen have been found to be highly correlated and nitrate–nitrogen has been the dominant form, constituting nearly 90% of nitrogen (Aronsson & Stenberg, 2010). For leaching calculations, daily values of measured drainage runoff were multiplied by daily values of nitrate concentration, obtained through linear interpolation between sampling dates.

## 2.7 | Yield

Yield was measured plot-wise at all cuts, by weighing the fresh weight on a 15m<sup>2</sup> area within each plot and multiplying by the dry matter content. Plant samples were taken plot-wise for determination of dry matter content and nitrogen content according to the Dumas method on a LECO CNS-2000 (Leco Corp., St Joseph, MI, USA; Kirsten & Hesselius, 1983). Samples for determination of feed value (energy, protein and neutral detergent fibre (NDF)) were taken treatment-wise for each ley type. Samples for botanical analysis were taken treatment-wise in the grass–clover ley, and dry weight of the grass, clover and herb fractions was determined.

## 2.8 | Nitrogen fixation

Symbiotic nitrogen fixation in the grass–clover leys was estimated from clover density, harvested biomass and nitrogen content in each treatment, using an empirical model designed to estimate nitrogen fixation in leguminous crops (Høgh-Jensen, Loges, Jensen, Jørgensen, & Vinther, 1998;

Høgh-Jensen, Loges, Jørgensen, Vinther, & Jensen, 2004). In this model, the amount of N<sub>2</sub> fixed in the shoot mass of a legume is corrected proportionately for the amounts of fixed N<sub>2</sub> found below defoliation height, transferred to other species and immobilized in the soil in partly decomposed organic matter.

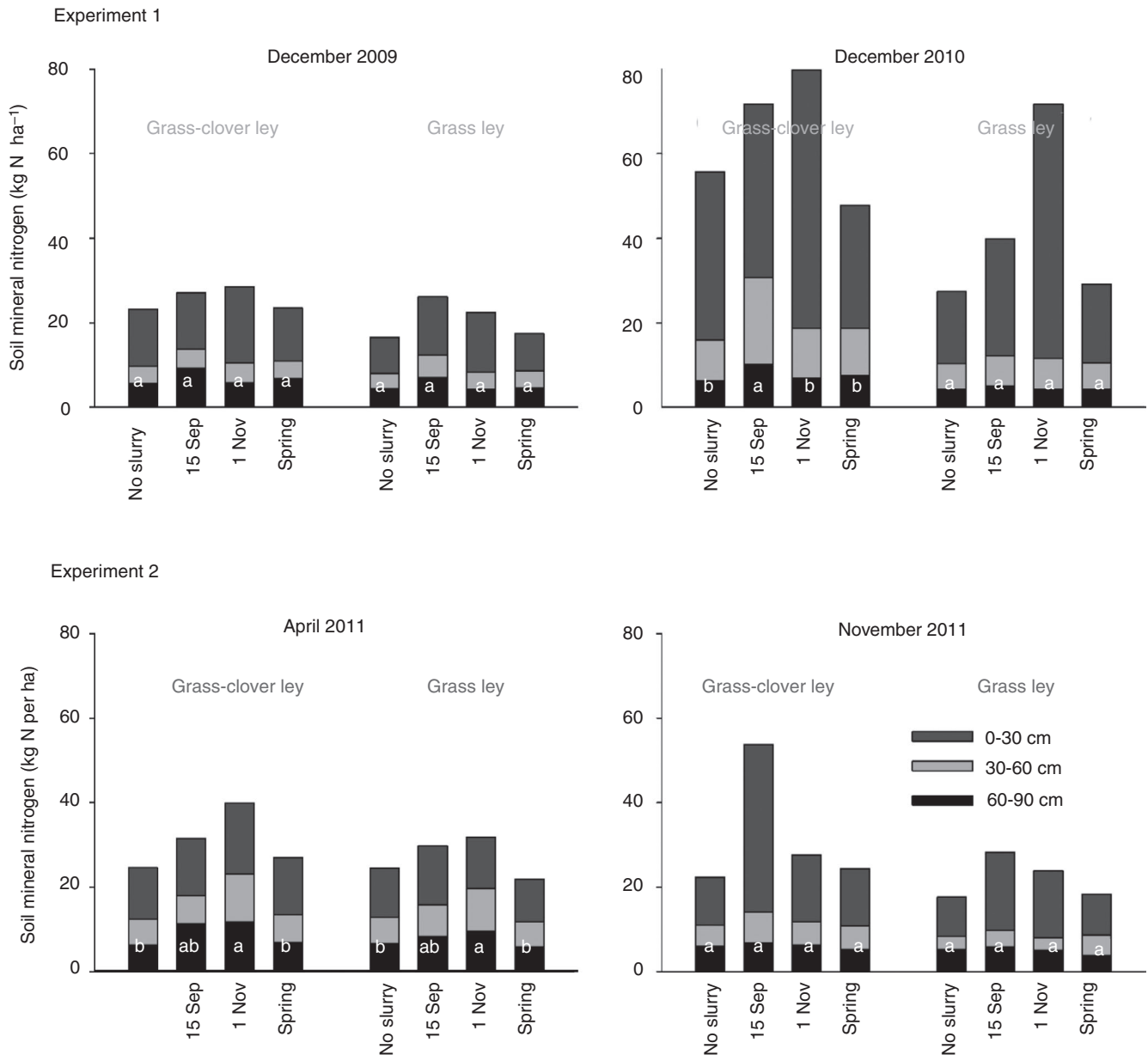
## 2.9 | Statistical analyses

Differences between treatments of all plot-wise collected data were tested statistically with one-way ANOVA (general linear model), followed by Tukey comparison test (Minitab, Ltd., Coventry, UK). A general linear model (which gives equal results to balanced ANOVA if the data are balanced) was used to analyse datasets with missing values in some plots, which was the case for water sampling by suction cups in one of the plots with grass ley. Comparisons were made between the slurry treatments within ley type, experiment and year and, when relevant, also for all experiments and years together. Since the blocks with each ley type were kept together instead of being randomized, the design did not allow for statistical comparisons between ley types. However, since the ley types were expected to differ, they were analysed and presented separately.

## 3 | RESULTS

### 3.1 | Plant nitrogen

Aboveground plant nitrogen concentration in November 2009 (just before the second slurry application to the first two-year ley) was significantly higher (~40 kg N ha<sup>-1</sup>) in plots with early autumn slurry application than in the other treatments in grass and grass–clover ley (20 and 25–30 kg N ha<sup>-1</sup>, respectively) (Figure 2a). After winter, in April 2010, aboveground plant nitrogen concentration had decreased in all treatments, but was around 10 and 5 kg N ha<sup>-1</sup> higher in the early and late autumn-manured treatments, respectively, than in the unmanured treatments (Figure 2b). In November 2011, differences



**FIGURE 3** Soil mineral nitrogen content in the subsoil in late autumn (or early spring) in the different treatments and years in experiments 1 and 2. Different letters on bars within each ley type, experiment and year indicate significant differences in soil mineral content in subsoil (30–90 cm depth) ( $p < .05$ ; ANOVA followed by Tukey test)

in aboveground plant nitrogen between the treatment with no slurry and the treatment with slurry applied in September 2011 (Figure 2c) were similar to those in 2009 (Figure 2a), but differences between the different slurry treatments were smaller and not statistically significant in grass ley.

### 3.2 | Soil mineral nitrogen

Soil mineral nitrogen ( $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$ ) levels in the whole soil profile (0–90 cm) in autumn-manured treatments were compared with those in unmanured treatments, to assess how much of the slurry nitrogen applied remained as

mineral nitrogen in soil. In December, the levels were on average  $15 \text{ kg N ha}^{-1}$  higher ( $p < .001$ ) in the autumn-manured treatments than in the other treatments (data not shown), which represents around 25% of the amount added as ammonium nitrogen in slurry. In the grass ley, there was a difference between early and late autumn application, with  $19 \text{ kg N ha}^{-1}$  more soil mineral nitrogen in the late autumn-manured treatment and  $11 \text{ kg N ha}^{-1}$  more in the early autumn-manured treatment compared with the unmanured treatment ( $p = .002$ ). Soil mineral nitrogen level in the subsoil (30–90 cm; Figure 3) is the part of the soil mineral nitrogen that has migrated down the profile and poses a high risk of nitrate leaching. It was on average  $4.9 \text{ kg N}$

$\text{ha}^{-1}$  higher in the treatment with early autumn application compared with the unmanured treatment when samples taken in late autumn from all experiments were analysed together ( $p = .025$ ). However, on analysing each experiment separately, the difference was only significant at the sampling in December 2010 in grass-clover ley (Figure 3). At the sampling in April 2011, when some time had elapsed after the late autumn application, the mineral nitrogen level in subsoil in that treatment was significantly elevated, by around  $9 \text{ kg N ha}^{-1}$ , compared with the unmanured treatment (Figure 3).

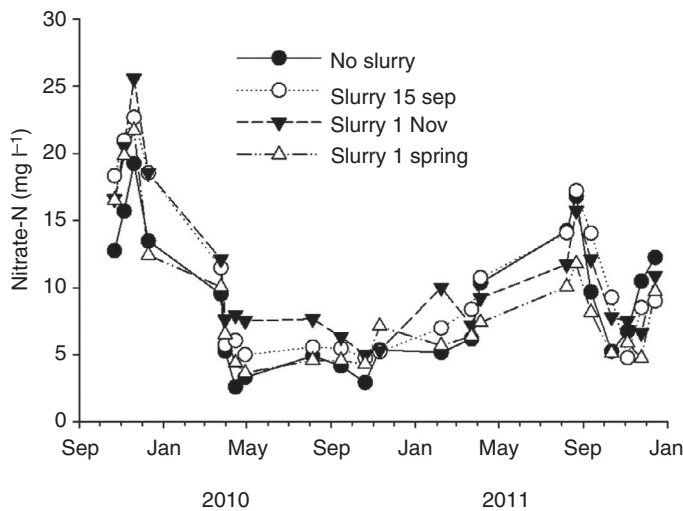
### 3.3 | Nitrate leaching

The nitrate concentration in soil water samples from the grass-clover ley varied from 1 to  $25 \text{ mg L}^{-1}$  during both years of the experiments (Figure 4a,c). In the grass ley, the

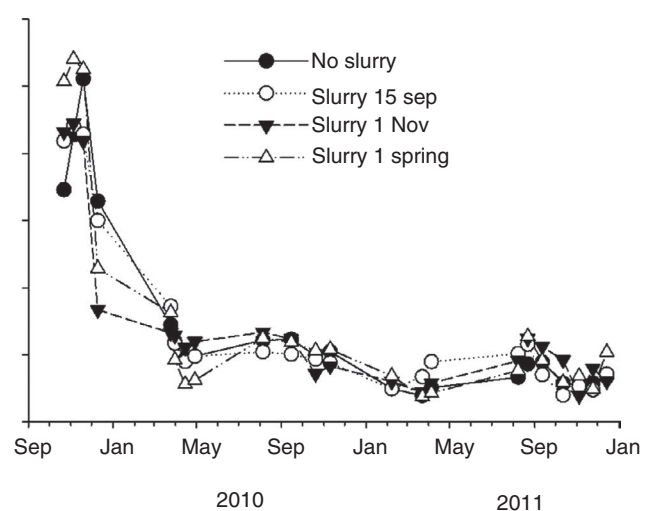
nitrate concentration showed similar variation as in grass-clover ley during the first year, but remained below  $10 \text{ mg L}^{-1}$  during the second year of the experiments (Figure 4b,d). During some periods, there were significantly higher concentrations in the two autumn-manured treatments. In the grass-clover ley blocks in experiment 1 (sown 2009), nitrate concentration in sampled water in April–May 2010 and in February 2011 was significantly higher, by around  $5 \text{ mg L}^{-1}$  ( $p = .004$ – $.03$ ), in the treatment with late autumn slurry application than in the unmanured treatment (Figure 4a). In the grass ley blocks, the early autumn-manured treatment had significantly ( $p = .002$ – $.016$ ) higher nitrate concentrations in sampled water in April–August 2011, but the difference compared with the unmanured treatment was only around  $1 \text{ mg L}^{-1}$  (Figure 4b).

In the grass-clover ley blocks in experiment 2 (sown 2010), the nitrate concentration in sampled water from the

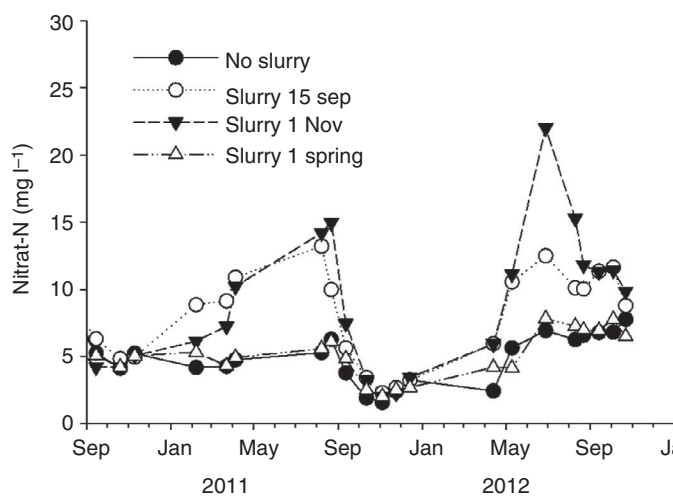
(a) Grass-clover ley, experiment 1



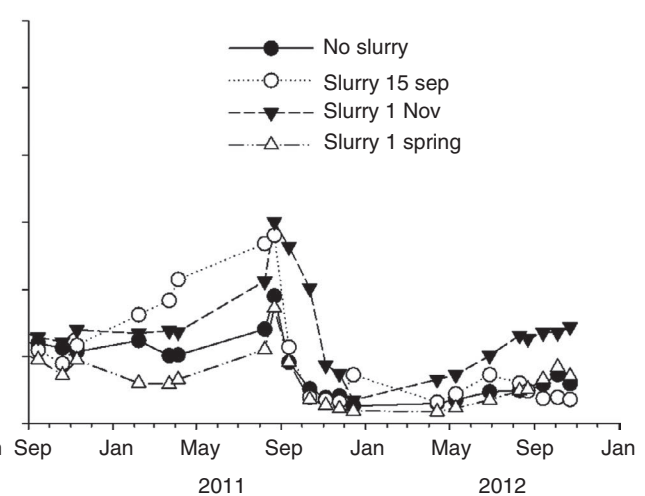
(b) Grass ley, experiment 1



(c) Grass-clover ley, experiment 2



(d) Grass ley, experiment 2



**FIGURE 4** Nitrate–nitrogen concentration in soil water at 80 cm depth in the different treatments and sward types in experiments 1 and 2

early autumn-manured treatment was significantly higher, by around  $5 \text{ mg L}^{-1}$  ( $p = .000-.03$ ), than in the unmanured treatments in February–April and October 2011 and in May 2012 (Figure 4c). It was also significantly higher, by around  $5-15 \text{ mg L}^{-1}$  ( $p = .01-.02$ ), in the late autumn-manured treatment in April, late August and September 2011 and in May–August 2012 than in the unmanured treatment (Figure 4c). In the grass ley blocks, water samples from the treatment with early autumn slurry application had significantly ( $p = .005-.03$ ) higher concentrations of nitrate, by around  $5 \text{ mg L}^{-1}$ , than in the unmanured treatment in March–August 2011 (Figure 4d), but there were no significant differences during 2012.

The measured discharge used for calculations varied from 266 mm in the first year to 349 mm in the last year (Figure 5), with 162–184 mm in the period October–March, when grass growth is limited. In 2009/2010, the peak discharge during this period was in March, whereas in 2010/2011 and 2011/2012 more of the runoff occurred during October–January (Figure 5). The rainfall/runoff ratio was 1.7 during the first winter (October 2009–March 2010) and 0.9 during the next two winters and 3–5 during the summers. Yearly nitrate leaching was on average  $22-23 \text{ kg N ha}^{-1}$  in the treatments with slurry application in autumn (Table 3), which was  $5-6 \text{ kg N ha}^{-1}$  more than in the other treatments. However, the difference varied from 0 to  $10 \text{ kg N ha}^{-1}$  between experiments and years, and was only significant for the second experiment (Table 3). There was no significant difference in nitrate leaching between early and late autumn application in either experiment. Nitrate leaching from grass ley was lower in the second year in both experiments (Table 3). Slurry application in spring did not lead to elevated nitrate leaching in either experiment (Table 3).

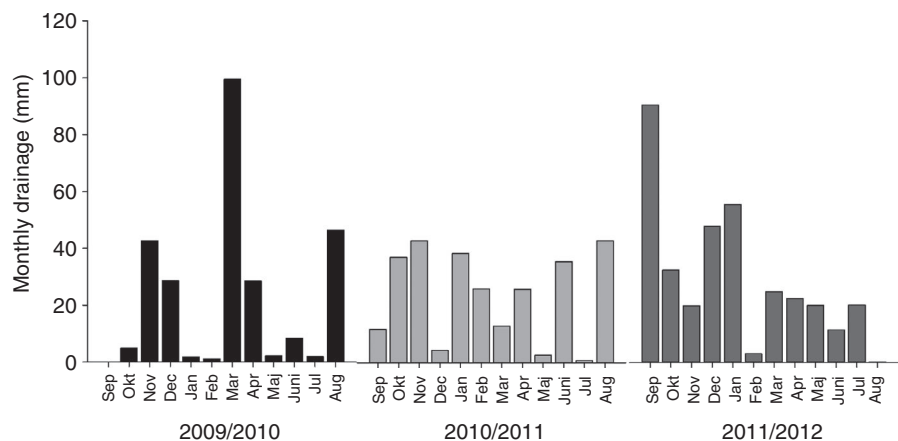
### 3.4 | Yield and feed quality

There were no differences in dry matter yield between treatments, except that the spring-manured treatment in 2011

(with a higher slurry rate; Table 2) had significantly higher total yield than the other treatments. Forage quality (energy, NDF and protein) was also similar between treatments (data not shown), although there was some variation between ley types and cuts (not statically analysed). In experiment 1, total grass–clover ley yield was approximately  $11 \text{ t dry matter ha}^{-1} \text{ year}^{-1}$  and total grass ley yield was approximately  $9 \text{ t dry matter ha}^{-1} \text{ year}^{-1}$ , resulting in  $273 \text{ kg N ha}^{-1}$  and  $149 \text{ kg N ha}^{-1}$  nitrogen offtake in the grass–clover and grass ley, respectively. In experiment 2, total grass–clover ley yield was approximately  $12-13 \text{ t ha}^{-1}$  in the first year and  $13-14 \text{ t ha}^{-1}$  in the second year, while the grass ley yield was  $9 \text{ t ha}^{-1}$  and  $11-12 \text{ t ha}^{-1}$ , respectively. In both ley types, nitrogen offtake with yield in the second two-year ley was around  $10 \text{ kg N ha}^{-1}$  higher than in the first. Clover density in the grass–clover ley was on average 30% of dry matter, without any obvious differences between treatments. Weed density (herbs) was around 1–3% of dry matter.

### 3.5 | Nitrogen balance

Nitrogen fixation in the grass–clover ley, calculated from the clover density, amounted to around  $50 \text{ kg N ha}^{-1}$  per cut, or  $150 \text{ kg N ha}^{-1} \text{ year}^{-1}$  (Table 4). Based on that and the results presented above, together with estimated ammonia emissions of 40% of manure ammonium nitrogen (Rodhe, Pell, & Yamulki, 2006), around  $50 \text{ kg N ha}^{-1}$  was unaccounted for in treatments with slurry, which is in line with the amount of organic nitrogen added with slurry. Leaching losses in  $\text{kg N ha}^{-1}$  were lower from the grass ley, but the nitrogen inputs and dry matter yield were also lower. Leaching was 12–13% in grass ley and 8% in grass–clover ley relative to both mineral nitrogen input and nitrogen removed by harvest. However, the grass–clover ley had a larger nitrogen surplus, which could be subject to leaching later on. In both ley types, the lowest leaching in relation to total nitrogen input was from the treatment with slurry applied in April.



**FIGURE 5** Measured discharge values used for calculations, presented per month in the three different years of the study



**TABLE 3** Nitrate–nitrogen leaching ( $\text{kg N ha}^{-1}$ ) in each experiment, sward type and year

Experiment	Experiment 1					Experiment 2					Both
	Grass–clover		Grass		Both	Grass–clover		Grass		Both	Both
Year	09/10	10/11	09/10	10/11	Both	10/11	11/12	10/11	11/12	Both	All
n	4	4	3	3	14	4	4	3	3	14	28
No slurry	27 <sup>a</sup>	20 <sup>a</sup>	31 <sup>a</sup>	8 <sup>a</sup>	21 <sup>a</sup>	14 <sup>b</sup>	12 <sup>b</sup>	17 <sup>a</sup>	9 <sup>a</sup>	12 <sup>b</sup>	18 <sup>b</sup>
Slurry 15 Sept	33 <sup>a</sup>	22 <sup>a</sup>	29 <sup>a</sup>	9 <sup>a</sup>	23 <sup>a</sup>	23 <sup>a</sup>	20 <sup>ab</sup>	24 <sup>a</sup>	12 <sup>a</sup>	19 <sup>a</sup>	23 <sup>a</sup>
Slurry 1 Nov	37 <sup>a</sup>	22 <sup>a</sup>	26 <sup>a</sup>	9 <sup>a</sup>	24 <sup>a</sup>	23 <sup>a</sup>	24 <sup>a</sup>	23 <sup>a</sup>	21 <sup>a</sup>	20 <sup>a</sup>	24 <sup>a</sup>
Slurry 1 April	29 <sup>a</sup>	17 <sup>a</sup>	29 <sup>a</sup>	8 <sup>a</sup>	21 <sup>a</sup>	14 <sup>b</sup>	14 <sup>ab</sup>	15 <sup>a</sup>	11 <sup>a</sup>	12 <sup>b</sup>	18 <sup>b</sup>
<i>p</i> -value	.61	.18	.87	.59	.61	.002	.024	.05	.12	.001	<.001

Note: Means with different letters are significantly different ( $p < .05$ , ANOVA followed by Tukey test).

Input	Slurry	Grass–clover sward				Grass sward				
		No	15 Sep	1 Nov	1 Apr	No	15 Sep	1 Nov	1 Apr	
Manure, organic nitrogen		0	45	48	60	0	45	48	60	
Manure, inorganic nitrogen		0	63	56	69	0	63	56	69	
Mineral fertilizer		165	125	125	125	165	125	125	125	
Nitrogen fixation <sup>a</sup>		148	150	156	137	0	0	0	0	
Sum		313	382	384	390	165	233	229	254	
Output										
Leaching		18	24	26	19	16	19	20	16	
Ammonia emissions <sup>b</sup>		0	25	22	28	0	25	22	28	
Nitrogen offtake with harvest		284	276	274	280	144	145	152	178	
Sum		302	326	322	326	160	189	194	222	
Difference		11	57	62	64	5	44	35	32	

<sup>a</sup>Calculated from clover density and dry matter yield according to Høgh-Jensen et al. (2004).

<sup>b</sup>Assuming that 40% of the ammonium in slurry was emitted.

**TABLE 4** Nitrogen balance in the different treatments on grass–clover and grass swards (mean of two experiments and two years)

autumn, around  $20 \text{ kg N ha}^{-1}$  more mineral nitrogen was found in soil than in the treatment without slurry application (Figure 3). Since  $50\text{--}60 \text{ kg N ha}^{-1}$  were added with slurry (Table 2), this means that around half the mineral nitrogen input was not recovered in either the soil or above-ground crop. To calculate the nitrogen balance (Table 4), it was estimated that 40% (Rodhe et al., 2006), or around  $25 \text{ kg N ha}^{-1}$ , was lost as ammonia emissions, which seems reasonable since that would account for most of the missing nitrogen. In addition, some mineral nitrogen could have been assimilated by roots or immobilized by microorganisms in the soil (Sturite, Henriksen, & Breland, 2007), and was therefore present as organic nitrogen at the time of soil sampling. The results indicated that, due to the limited plant

## 4 | DISCUSSION

### 4.1 | Nitrogen flows during autumn

The nitrogen measurements in soil and plants during autumn indicated the proportions of slurry nitrogen applied that were taken up by the crop, remained in soil or presumably emitted to air, lost with drainage water or incorporated into soil organic matter. In the treatments with slurry application in early autumn to grass ley, in late autumn around  $10 \text{ kg N ha}^{-1}$  more mineral nitrogen was present in the soil (Figure 3) and  $20 \text{ kg N ha}^{-1}$  more nitrogen was recovered in plant biomass (Figure 2) compared with the unmanured treatment. In the treatment with slurry application in late

uptake during autumn, both application times in autumn supplied mineral nitrogen that could leach from the soil during winter, even though the amount was half as much in the early slurry application treatment due to plant uptake. On the other hand, some of the nitrogen provided in the early application had already moved to the subsoil by December (Figure 3).

## 4.2 | Nitrogen balance in total

In both ley types, there was a surplus of nitrogen according to the soil balance calculations (Table 4). In the grass leys, this surplus was similar to or less than the amount applied as organic nitrogen with slurry. Much of that cannot be expected to be available as mineral nitrogen during the first year after application (Delin & Engström, 2010). In the grass–clover leys, the surplus was higher. This could have been incorporated into the soil organic matter formed from the root mass of the ley crop. In addition, nitrogen deposition or denitrification was not accounted for in calculating nitrogen balances. Nitrogen deposition in the area is reported to be around  $6 \text{ kg N ha}^{-1}$  (Pihl Karlsson, Akselsson, Hellsten, Karlsson, & Malm, 2010). Denitrification is probably limited due to the free-draining soil and could be of similar magnitude to deposition. The total input and output per year and the positive balance is in line with other reports. For instance, van Leeuwen et al. (2019) reported similar inputs ( $250\text{--}450 \text{ kg N ha}^{-1}$ ), outputs ( $200\text{--}350 \text{ kg N ha}^{-1}$ ) and nitrogen balance ( $50\text{--}120 \text{ kg N ha}^{-1}$ ). Bučienė, Švedas, and Antanaitis (2003) reported a field balance with similar amounts of nitrogen inputs with fertiliser application and outputs with grass harvests and nitrogen leaching as in our grass ley, but with some nitrogen fixation ( $60 \text{ kg N ha}^{-1}$ ) and also an estimated  $18 \text{ kg N ha}^{-1}$  deposition and  $29 \text{ kg N ha}^{-1}$  denitrification.

## 4.3 | Leaching losses in relation to ammonia losses

There are several pathways for nitrogen losses from animal slurry after application to soil, including ammonia emissions, leaching and denitrification. Both nitrogen leaching and ammonia emissions pose a risk of eutrophication of surface waters in the environment. It was assumed here that 40% of the ammonium in slurry was emitted, based on observations in other studies applying cattle slurry on grassland (Rodhe et al., 2006). This indicates that leaching and ammonia emissions were of similar magnitude (Table 4) and that the differences in leaching between the different slurry application dates were small compared with the total nitrogen losses. Therefore, the risk of ammonia losses is just as important to

consider as the risk of elevated leaching. Ammonia losses are dependent on air temperature and wind speed, with nitrogen recovery in grass being higher after slurry application in cooler temperatures (Sommer & Hutchings, 2001). Since temperatures are usually lower in late autumn than earlier in autumn, restricting slurry application to early autumn could be a poor alternative in terms of total nitrogen losses, unless ammonia emissions are minimized through other measures, such as slurry incorporation into soil or acidification (Webb et al., 2013).

## 4.4 | Importance of slurry dose

The increased nitrate leaching from autumn slurry application compared with application of slurry or mineral fertilizer in spring constituted on average 7% of total nitrogen applied with slurry. This is slightly less than in a study in the UK by Smith et al. (2002), who found that slurry application increased leaching by 15–20% of the amount of nitrogen supplied with slurry applied in October and November compared with no slurry application or application in January. However, larger amounts of nitrogen ( $72\text{--}128 \text{ kg NH}_4\text{-N ha}^{-1}$ ) were applied in their study. Since nitrogen uptake by grass during autumn is estimated to be limited to  $40\text{--}55 \text{ kg N ha}^{-1}$  under Swedish conditions (Aronsson & Torstensson, 2004), the more this limit is exceeded, the larger the leachable fraction of applied nitrogen. The amount of nitrogen applied can thus be expected to have an effect on nitrate leaching (Kayser, Breitsameter, Benke, & Isselstein, 2015), especially if the capacity of the grass to take up nitrogen is exceeded. In this study, significantly higher nitrate leaching after autumn application of slurry was observed only in experiment 2, possibly because higher doses of slurry were applied in that experiment (Table 2). However, in the year when the two experiments ran in parallel (2010/2011), there were still significant differences in experiment 2, but not in experiment 1. The nitrogen yield in the unmanured treatment was almost identical in the two experiments in that period, indicating that the nitrogen status of the soil was very similar. Therefore, the difference between the experiments cannot only be attributed to slurry dose and perhaps to the higher clover content in the ley in experiment 1 (on average 36%) compared with experiment 2 (27%), if higher nitrogen fixation levelled out differences between the treatments.

## 4.5 | Differences between sites

The risk of leaching may differ widely between sites, due to differences in soil texture and climate conditions affecting crop growth and drainage throughflow. The elevated leaching from autumn-applied slurry observed for the

coarse-textured soil at our study site could be prevented on a soil with higher clay content. For instance, at four sites in England with freely drained loam soils, Smith et al. (2002) found higher nitrogen leaching losses following slurry application to grassland in September–November compared with application in June, December and January. On heavy clay soils in England, Sagoo et al. (2006) found no difference in nitrogen leaching between application dates. In the study by Smith et al. (2002), there were differences between sites depending on precipitation and drainage amounts after slurry application, with the risk of leaching being lower at sites with lower drainage throughflow. However, even when climate and soil texture are similar, the leaching risk can differ. For example, in a Swedish study conducted during the same period as the present study and at a site 260 km south-west of our study site, but with similar soil texture, slurry rate and precipitation, there was no indication of elevated leaching following autumn application of slurry to ley (Torstensson, Aronsson, & Ekre, 2012). The reason for this discrepancy is not obvious, but could possibly be related to higher levels of mineral nitrogen in the soil at our study site than at the site used in their study, indicating that our soil provides more mineral nitrogen and that less nitrogen needs to be added to exceed the plant assimilation rate. However, the difference in leached nitrate concentration could also be related to different sampling methods, since with suction cups at 80 cm (as in the present study) plants might still take up nitrogen below this depth, and leaching may be overestimated. With sampling of water from separate tile-drained plots, as in the study by Torstensson et al. (2012), leaching may instead be underestimated, since some leaching may occur outside the drainage system.

#### 4.6 | Leaching depending on ley type and year

Due to nitrogen fixation by clover, a clover-rich ley will naturally contain more nitrogen than a pure grass ley if both sward types receive similar amounts of nitrogen fertilizer (Ohlander, Bergkvist, Stendahl, & Kvist, 1996). With more nitrogen present, there is a higher risk of nitrogen leaching. In this study, leaching from grass ley in the second year of both experiments was only about half that from grass–clover ley or from first-year grass ley. The small difference between sward types in the first year could probably be explained by the higher production and nitrogen uptake with the grass–clover mixture than with the pure grass ley balancing up the higher nitrogen input (Table 4). However, in the second year, it is likely that plant litter from the first year affected microbial immobilization in soil, which can be expected to be higher in the grass ley due to the higher C/N ratio of grass than clover (de Neergaard, Hauggaard-Nielsen, Jensen, &

Magid, 2002). This may have limited the amount of nitrogen available for leaching in the grass ley during the second year. Soil mineral nitrogen content in subsoil in autumn can be a reasonably good predictor of nitrate leaching (Delin & Stenberg, 2014; Kayser et al., 2015).

## 5 | CONCLUSIONS

This study showed that nitrogen leaching can be higher after application of slurry in autumn compared with application in spring, especially when the crop is already well supplied with nitrogen from other sources such as nitrogen fixation by clover. It also indicated a tendency for higher leaching after late (November) compared with early (September) autumn application, but the differences between these application times were not significant. Therefore, timing of slurry application in autumn does not seem to be important, meaning that regulations allowing application in early autumn, but not in late autumn, will probably not have any significant effect on leaching. It is probably more important to limit the amount of slurry applied in autumn and to consider the risk of other nitrogen losses that may vary more between application times, such as ammonia volatilization.

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### REFERENCES

- Albertsson, B. (1997). Spridningstidpunkter för stallgödsel till vall. Försöksrapport 1997. Sammanställning av resultat från växtodlingsförsök utförda 1996 i O, Pn, Ps, R och S-län, samt medeltal för flera år. Försök i Väst, Hushållningssällskapet, Skara, p. 21–22. (In Swedish)
- Albertsson, B. (1998). Spridningstidpunkter för stallgödsel till vall. Försöksrapport 1998. Sammanställning av resultat från växtodlingsförsök utförda 1997 i O, Pn, Ps, R och S-län, samt medeltal för flera år. Försök i Väst, Hushållningssällskapet, Skara, p. 22. (In Swedish)
- Andersson, P.-A. (2002). Effekt av höstspridd flytgödsel till vall. Rapport från växtodlings- och växtskydds dagar i Växjö den 11 och 12 december 2002. Meddelande från Södra Jordbruksförsöksdistriktet, nr 55 (2002), p. 22:1–2. (In Swedish)
- Aronsson, H., & Stenberg, M. (2010). Leaching of nitrogen from a 3-year grain crop rotation on a clay soil. *Soil Use and Management*, 26, 274–285.

- Aronsson, H., & Torstensson, G. (2004). *Beräkning av olika odlingsåtgärders inverkan på kväveutlakningen*. SLU, Uppsala. Avd. för vattenvårdslära. Ekohydrologi 78 (In Swedish).
- Bučienė, A., Švedas, A., & Antanaitis, Š. (2003). Balances of the major nutrients N, P and K at the farm and field level and some possibilities to improve comparisons between actual and estimated crop yields. *European Journal of Agronomy*, 20, 53–62.
- Delin, S., & Engström, L. (2010). Timing of organic fertiliser application to synchronise nitrogen supply with crop demand. *Acta Agriculturae Scandinavica. Section B, Soil and Plant Science*, 60, 78–88.
- Delin, S., & Stenberg, M. (2014). Effect of nitrogen fertilization on nitrate leaching in relation to grain yield response on loamy sand in Sweden. *European Journal of Agronomy*, 52, 291–296.
- Delin, S., & Stenberg, M., Nyberg, A., & och Brohede, M. (2012). Potential methods for estimating nitrogen fertilizer value of organic residues. *Soil Use and Management*, 28, 283–291.
- Djurhuus, J., & Jacobsen, O.H. (1995). Comparison of ceramic suction cups and KCl extraction for the determination of nitrate in soil. *European Journal of Soil Science*, 46, 387–395.
- Eastin, E. F. (1978). Use of an AutoAnalyzer for total nitrogen determination in plants. *Communications in Soil Science and Plant Analysis*, 9, 107–113.
- EEC. (1991). Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources.
- Hallin, O., & Jansson, J. (2002). *Effekt av höstpridd flytgödsel till vall. Mellansvenska Försökssamarbetet, Försöksrapport 2001*, 79–82. (In Swedish)
- Hoekstra, N., Lalor, S., Richards, K., O'Hea, N., Lanigan, G., Dyckmans, J., Schulte, R. P. O., & Schmidt, O. (2010). Slurry  $^{15}\text{NH}_4\text{-N}$  recovery in herbage and soil: Effects of application method and timing. *Plant and Soil*, 330, 357–368.
- Høgh-Jensen, H., Loges, R., Jensen, E. S., Jørgensen, F. V., & Vinther, F. P. (1998). Empirisk model til kvantificering af symbiotisk kvælstoffiksering i bælglplanter. In E. S. Kristensen & J. E. Olesen (Eds.), *Kvælstofudvaskning og –balancer i konventionelle og økologiske produktionssystemer* (pp. 69–86). Tjele, Danmark: Forskningscenter for Økologisk Jordbrug (FØJO). (In Danish)
- Høgh-Jensen, H., Loges, R., Jørgensen, F., Vinther, F., & Jensen, E. S. (2004). An empirical model for quantification of symbiotic nitrogen fixation in grass-clover mixtures. *Agricultural Systems*, 82, 181–194.
- Huijsmans, J. F. M., Vermeulena, G. D., Holb, J. M. G., & Goedhart, P. W. (2018). A model for estimating seasonal trends of ammonia emission from cattle manure applied to grassland in the Netherlands. *Atmospheric Environment*, 173, 231–238.
- Kayser, M., Breitsameter, L., Benke, M., & Isselstein, J. (2015). Nitrate leaching is not controlled by the slurry application technique in productive grassland on organic-sandy soil. *Agronomy for Sustainable Development*, 35, 213–223.
- Kirsten, W. J., & Hesselius, G. U. (1983). Rapid automatic, high capacity Dumas determination of nitrogen. *Microchemistry Journal*, 28, 529–547.
- Lalor, S. T. J., Schröder, J. J., Lantinga, E. A., Oenema, O., Kirwan, L., & Schulte, R. P. O. (2011). Nitrogen Fertilizer Replacement Value of Cattle Slurry in Grassland as Affected by Method and Timing of Application. *Journal of Environmental Quality*, 40, 362–373.
- Larsen, K. E. (1987). *NKJ-projekt 55 "Husdyrgødningens udnyttelse i planteproduktion ved intensivt husdyrhold"*. Virkning af forskellige udbringningsmåder og -tidspunkter for gylle. In: Hus-dyrgødningens virkninger på jord og avling. NJF-seminarium nr 113, NJF-utredning/rapport nr 39, 36–48. (In Danish).
- van Leeuwen, M. M. W. J., van Middelaar, C. E., Oenema, J., van Dam, J. C., Stoorvogel, J. J., Stoof, C. R., & de Boer, I. J. M. (2019). The relevance of spatial scales in nutrient balances on dairy farms. *Agriculture, Ecosystems and Environment*, 269, 125–139.
- Lindén, B. (2008). *Flytgödselspridning på hösten: möjligheter att minska kväveutlakningsriskerna genom olika åtgärder i växtodlingen. Litteraturoversikt: kunskapsläge och kunskapsluckor. Precisionsodling 2008:2*. (In Swedish)
- Liu, J., Kleinman, P. J. A., Aronsson, H., Flaten, D., McDowell, R. W., Bechmann, M., Beegle, D. B., Robinson, T. P., Bryant, R. B., Liu, H., Sharpley, A. N., & Veith, T. L. (2018). A review of regulations and guidelines related to winter manure. *Ambio*, 47, 657–670.
- Malhi, S. S., & McGill, W. B. (1982). Nitrification in three Alberta soils: Effect of temperature, moisture and substrate concentration. *Soil Biology and Biochemistry*, 14, 393–399.
- Mulvaney, R. L. (1996). Nitrogen – inorganic forms. In D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Leppert, P. H. Soltanpour, M. A. Tabatabai, C. T. Johnson, & M. E. Sumner (Eds.), *Methods of Soil Analysis, Part 3-Chemical Methods*, pp. 1123–1184. Soil Science Society of America Book Series, Nr 5. Wisconsin, USA: American Society of Agronomy and Soil Science Society of America.
- de Neergaard, A., Hauggaard-Nielsen, H., Jensen, L. S., & Magid, J. (2002). Decomposition of white clover (*Trifolium repens*) and ryegrass (*Lolium perenne*) components: C and N dynamics simulated with the DAISY soil organic matter submodel. *European Journal of Agronomy*, 16, 43–55.
- Ohlander, L., Bergkvist, G., Stendahl, F., & Kvist, M. (1996). Yield of catch crops and spring barley as affected by time of undersowing. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, 46, 161–168.
- Pihl Karlsson, G., Akselsson, C., Hellsten, S., Karlsson, P. E., & Malm, G. (2010). *Övervakning av luftföroreningar i västra götlands län – mätningar och modellering*. IVL rapport B 1844. 20 pp. (In Swedish)
- Rammer, C., Lingvall, P., & Salomon, E. (1997). Ensiling of manured crops - Does repeated spreading of slurry increase the hygienic risk? *Journal of the Science of Food and Agriculture*, 73, 329–336.
- Rodhe, L., Pell, M., & Yamulki, S. (2006). Nitrous oxide, methane and ammonia emissions following slurry spreading on grassland. *Soil Use and Management*, 22, 229–237.
- Sagoo, E., Williams, J. R., Chambers, B. J., Cross, R., Short, J., Portwood, A., & Hodgkinson, R. A. (2006). *Nitrogen and phosphorus losses following cattle slurry applications to a drained clay soil at Brimstone Farm*. In: Petersen, S. O. (Ed) 12th Ramiran International Conference. Technology for Recycling of Manure and Organic Residues in a Whole-Farm Perspective. Vol. II, Aarhus, Denmark, 11–13 September 2006. DIAS Report 12, 285–287.
- Smith, K. A., Beckwith, C. P., Chalmers, A. G., & Jackson, D. R. (2002). Nitrate leaching following autumn and winter application of animal manures to grassland. *Soil Use and Management*, 18, 428–434.
- Sommer, S. G., & Hutchings, N. J. (2001). Ammonia emission from field applied manure and its reduction—invited paper. *European Journal of Agronomy*, 15, 1–15.

- Sturite, I., Henriksen, T. M., & Breland, T. A. (2007). Winter losses of nitrogen and phosphorus from Italian ryegrass, meadow fescue and white clover in a northern temperate climate. *Agriculture, Ecosystems and Environment*, *120*, 280–290.
- Torstensson, G., Aronsson, H., & Ekre, E. (2012). *Växtnäringsutlakning i samband med spridning av flytgödsel till vall på hösten*. (Plant nutrient leaching in connection to slurry application to ley in autumn) Ekohydrologi 133. Swedish University of Agricultural Sciences, Uppsala. 10 pp. (In Swedish)
- Webb, J., Sørensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, P., & Reid, J. (2013). An

assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase manure-N efficiency. *Advances in Agronomy*, *119*, 371–442.

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