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REGULAR ARTICLE

Slurry $^{15}NH_4$-N recovery in herbage and soil: effects of application method and timing

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Abstract The effects of slurry application method and weather conditions after application on ammonia volatilisation are well documented, however, the effect on slurry N recovery in herbage is less evident due to large variability of results. The objective of this field experiment was to determine the recovery of cattle slurry NH_4-N in herbage and soil in the year of application as affected by application method (trailing shoe versus broadcast) and season of application (spring versus summer), using ^{15}N as a tracer. In 2007 and 2008, ^{15}N enriched slurry was applied on grassland plots. N recovery in herbage and soil during the year of application was determined. Both spring and trailing shoe application resulted in significantly higher herbage DM yields, N uptake and an increased recovery of $^{15}NH_4$-N in herbage. Additionally, the recovery of slurry $^{15}NH_4$-N in the soil at the end of the growing season was increased. Spring and trailing shoe application reduced the losses of slurry $^{15}NH_4$-N by on average 14 and 18 percentage points, respectively, which corresponded closely to ammonia volatilisation as predicted by the ALFAM model. It was concluded that slurry N recovery in temperate pasture systems can be increased by adjusting the slurry application method or timing.

Keywords Ammonia · Application method · Cattle slurry · Grassland · ^{15}N stable isotope tracer · Nitrogen recovery · Season · Trailing shoe

Introduction

Animal manure is a valuable resource of nutrients in north-western European grassland systems, however, manure application is often associated with nutrient losses to water and air (Schröder 2005a). The utilisation of slurry N is affected by a number of factors such as application method, timing and rate of application, and slurry composition. The largest loss pathway is ammonia volatilisation, and when crop uptake is limited this may be followed by leaching and some additional denitrification stimulated by the associated input of carbon (Rice et al. 1988; Schröder 2005a).

The implementation of the EU Nitrates Directive (91/676/EEC) (Anon 1991) has forced European

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farmers to improve the utilisation of manure derived nitrogen. In Ireland, approximately 80% of the manure produced by cattle is managed as slurry and its main application is on grassland (Hyde and Carton 2005). Irish legislation for compliance with the EU Nitrates Directive requires that from 2010, farm nutrient management plans are to include an assumed efficiency of 40% for nitrogen contained in cattle slurry (Anon 2006).

The most common form of slurry application in Europe is the use of a vacuum tanker with splash plate (Burton and Turner 2003), i.e. broadcast (BC) application. This is a relatively simple method and the equipment is inexpensive to purchase, maintain and operate (Ryan 2005). However, the associated high ammonia emissions (up to 90% of applied NH_4-N) can be substantially reduced by using low-emission application methods such as band spreading, trailing shoe application or injection (Malgeryd 1998; Misselbrook et al. 2002; Smith et al. 2000; Søgaard et al. 2002). For many grassland areas, the trailing shoe (TS) is considered to be the most effective alternative to broadcast application, as high stone content of soils and undulating topography make injection unsuitable.

Timing of slurry application is also important for maximising N recovery. Currently in Ireland, slurry is mostly applied in summer (Hyde and Carton 2005). Applications in autumn and winter can lead to high leaching losses (Ryan and Fanning 1996). On the other hand, summer applications may result in high N losses through ammonia volatilisation as a result of warmer, drier air and soil conditions (Schröder 2005a; Smith and Chambers 1993). Spring application generally results in lower losses as weather conditions are less conducive to volatilisation and the N requirement of the herbage is largest. In north-western Europe, spring application may be limited as soils are often too wet for slurry application using BC application. However, in a modelling study, Lalor and Schulte (2008) showed that in Ireland, the number of available spreading days is substantially higher where TS is used for slurry application. This was due to the fact that TS can be used to apply slurry under taller grass canopies while minimising sward damage and contamination (Laws and Pain 2002; Laws et al. 2002). Therefore, the TS allowed more flexible slurry application management in spring, as spreadland availability is less restricted by grass canopy heights on days when soil conditions are drier and more resistant to trafficking.

Numerous studies have reported significant effects of slurry application method and timing on ammonia volatilisation (Malgeryd 1998; Misselbrook et al. 2002; Rochette et al. 2008; Smith et al. 2000; Søgaard et al. 2002), however, most studies failed to find a significant corresponding increase in herbage yield or apparent N recovery (Misselbrook et al. 1996; Smith et al. 2000). In the present study, ^{15}N labelling of the slurry ammonium fraction made it possible to follow the fate of slurry N in the soil–plant system and simultaneously calculate losses through a mass balance approach. The slurry ammonium N fraction makes up approximately 50% of the slurry total N and is rapidly available for plant uptake, and therefore is considered the most important fraction for plant growth during the year of application (Schröder et al. 2007).

The objective of this field experiment was to determine the effect of application method and season of application on the recovery of cattle slurry ammonium N in herbage and soil in the year of application using ^{15}N as a tracer. It was hypothesised that 1) the N recovery and herbage yield following TS applied slurry would be higher compared to BC slurry due to reduced ammonia volatilisation; 2) the N recovery and herbage yield when delaying the TS application by 2 weeks would be higher due to reduced volatilisation as a result of the sheltering of the slurry by the taller sward canopy; and 3) the N recovery from slurry applied in spring would be higher than from slurry applied in summer as a result of reduced ammonia volatilisation due to more favourable weather conditions in spring.

Materials and methods

Experimental design

The experiment was situated in Johnstown Castle Research Centre, Wexford, Ireland, on a permanent grass sward, consisting mainly of perennial ryegrass on a fine loamy soil. The ^{15}N labelling study reported here was designed as a process-focused quantitative investigation complementing an agronomic experiment investigating the effect of cattle slurry application method and season on herbage N recovery using farm-scale equipment, as described by Lalor and Schulte (2007). In the 2 years of the present study (2007 and 2008), plots were situated directly adjacent to corresponding treatments in the agronomic experiment (Fig. 1). The land was used for grass silage in the year preceding the treatment application and the areas used in the two experimental years were adjacent to each other. The grass on all plots was cut to a height of 5 cm and removed prior to treatment application.

The experiment consisted of the following slurry treatments; 1) control plots which received no slurry (C); 2) simulated broadcast application on harvest stubble (BC); 3) simulated trailing shoe application on harvest stubble (TS1) and 4) simulated trailing shoe application delayed by 2 weeks to allow herbage growth (TS2). The four treatments were repeated for both spring and summer application timings (Table 1), giving a total of 8 treatments (4 application methods × 2 seasons) per year and each treatment combination had 6 replications. Within each treatment, two 80× 80 cm plots were established and the samples from the two plots were bulked before analyses (Fig. 1).

All plots received a blanket fertiliser application of P, K and S of 30, 250 and 40 kg ha^{-1}, respectively, at the start of each year. The plots with summer slurry treatment received 60 kg ha^{-1} of N fertiliser in April. The plots did not receive any fertiliser after slurry applications.

Slurry labelling and application

The slurry ammonium fraction was labelled by thoroughly mixing ^{15}N-labelled ammonium sulphate through the slurry, just before application. In order to minimise the associated increase in ammonium content and pH of the slurry (Chadwick et al. 2001), we used small quantities of highly ^{15}N enriched (99atom%) ammonium sulphate, aiming for a slurry ammonia-N enrichment of approximately 2atom% (Table 1).

In this experiment the same slurry was used as for the larger scale agronomy experiment (Lalor and Schulte 2007). Because of the large quantities required, the slurry was divided in several batches (of the same farm source).

Slurry was applied at the dates shown in Table 1, at a rate of 3.3 kg m^{-2} (33 t ha^{-1}). For the trailing shoe simulation, slurry was applied in bands on the ground using a watering can. Great care was taken to place the slurry underneath the grass canopy. Broadcast application was simulated by using a watering can fitted with a small disc to deflect the slurry. Slurry for each band (trailing shoe) and each plot (broadcast) was weighed into the watering cans. Slurry samples were taken for each block and stored in the freezer for further analysis.

Herbage and soil sampling

In 2007 and 2008, plots with spring applied slurry were harvested in May (first cut after slurry application), and in order to quantify the residual effect of slurry the plots were harvested again in July (second cut after slurry application) and early September (third cut after slurry application), respectively. Plots with summer applied slurry were harvested in July (first cut after slurry application) with a residual cut in

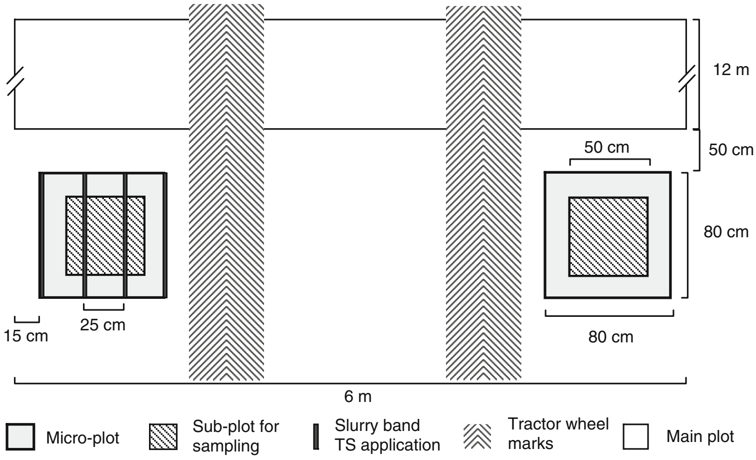

Fig. 1 Plot layout. The area surrounding the micro-plots did not receive any N fertilisation

Table 1 Slurry composition and weather conditions after application for different seasons and methods of application during 2007 and 2008

	2007								2008							
	Spring application				Summer application				Spring application				Summer application			
	BC & TS1[a]		TS2		BC & TS1		TS2		BC & TS1		TS2		BC & TS1		TS2	
Application date	04-Apr		18-Apr		06-Jun		25-Jun		02-Apr		16-Apr		04-Jun		18-Jun	
Slurry composition[b]																
DM content (g kg^{-1} DM)	59.1	(1.22)	61.7	(3.50)	69.3	(0.81)	67.2	(0.59)	74.7	(0.49)	67.3	(0.49)	78.9	(0.87)	79.5	(0.61)
N-total (g kg^{-1} DM)	53.3	(5.24)	50.7	(6.27)	48.4	(2.88)	48.5	(2.48)	38.9	(2.58)	36.8	(2.52)	31.9	(0.76)	30.3	(1.10)
N applied (kg N ha^{-1})	104	(8.6)	103	(11.3)	110	(6.9)	108	(4.7)	96	(6.5)	82	(5.9)	83	(1.4)	80	(3.2)
NH_4-N (g kg^{-1} DM)	24.7	(1.90)	22.6	(1.66)	15.7	(0.80)	17.3	(0.73)	24.0	(0.71)	22.8	(0.36)	13.6	(0.24)	13.9	(0.24)
NH_4-N applied (kg N ha^{-1})	48	(3.2)	46	(0.9)	36	(1.8)	38	(1.3)	59	(1.9)	51	(1.0)	35	(0.8)	36	(0.6)
NH_4-^{15}N (atom%)	2.7	(0.26)	2.6	(0.22)	2.1	(0.19)	3.4	(0.17)	1.8	(0.15)	1.9	(0.14)	2.7	(0.25)	2.6	(0.23)
Weather conditions during 24 hrs after application																
Mean temperature (°C)	8.5		10.3		13.4		12.5		11.4		7.7		11.3		12.1	
Mean wind speed (m s^{-1})	3.3		4.3		6.3		9.5		3.6		14.0		5.8		8.1	
Cum. rainfall (mm)	0		0		0		0		0		0		10		17	
Cum. radiation (J cm^{-2})	1,662		2,067		2,302		1,659		1,617		1,836		842		1,667	

[a] *BC* Broadcast; *TS1* Trailing shoe; *TS2* trailing shoe, 2 weeks delayed

[b] SD in parenthesis (*n*=6)

early September (second cut after slurry application) (Table 2).

Grass yields were determined by weighing the grass cut from a 50×50 cm quadrat within the plots' centre at 5 cm height using electric grass shears (Fig. 1). Soils were sampled at each harvest to a depth of 15 cm. Because of the banded slurry application it was important to ensure that the composite soil sample was representative of the slurry distribution in the whole plot in order to avoid under or overestimation of ^{15}N recovery in soil. It was assumed that the slurry density was 1 on the 3.5 cm wide slurry bands with a linear decrease to zero in the midpoint between bands, which resulted in an overall relative average slurry density of 0.6. Based on this, the number and location of the cores were chosen to achieve the same relative slurry density: Five cores (1.5 cm diameter) per plot were taken at regular distances (at 3, 13, 23, 33, 43 cm) within the 50× 50 cm inner square, resulting in 10 cores per replicate. Care was taken to avoid repeat sampling of the same area during the residual harvests.

Analytical procedures

Soils were sieved through a 2 mm screen before further analyses. Slurry, grass and soil dry matter content was determined by drying at 105°C overnight, which may have induced some C loss through volatilisation of volatile compounds from slurry (Derikx et al. 1994). Slurry total N was determined by Kjeldahl digestion of fresh slurry. Ammonium nitrogen (NH_4-N) was extracted from fresh slurry by shaking 10 g of slurry in 200 mL 0.1 M HCl on a peripheral shaker for 1 h and filtering through a No 2 Whatman filter paper. NH_4-N was determined in the

Table 2 Harvest dates and weather conditions during the growing periods for the first, second and third cut (spring only) after slurry application in 2007 and 2008

	2007			2008		
Spring application Summer application	First cut N.A.	Second cut First cut	Third cut Second cut	First cut N.A.	Second cut First cut	Third cut Second cut
Start date growing period	28-Mar	23-May	24-Jul	26-Mar	21-May	23-Jul
Harvest date	23-May	24-Jul	11-Sep	21-May	23-Jul	03-Sep
Mean temperature (°C)	11.5	13.8	15.3	9.8	13.7	15.3
Rain (mm day^{-1})	1.5	3.7	2.6	1.7	3.7	5.6
Radiation (J cm^{-2} day^{-1})	1,545	1,534	1,375	1,442	1,592	1,195

filtrate on an Aquakem 600 discreet analyser (Thermo Electron OY, Vantaa, Finland). Inorganic nitrogen, NH_4-N and total oxidised nitrogen (TON) (NO_3 and NO_2) in fresh soil were determined by extraction in 2 M KCl (40 g soil: 100 ml KCl, shaken for 1 h). NH_4-N and TON were determined in the extract on an Aquakem 600 discreet analyser. A sub-sample of the dried grass was milled through a 2 mm screen and subsequently ground to a fine powder in a ball mill. Total N and ^{15}N concentrations of the dried, milled grass and soil samples were measured on an ANCA 20/20 SL combustion isotope ratio mass spectrometer (IRMS) (Delta plus, Finnigan, Bremen, Germany). The ^{15}N isotopic enrichments of slurry and soil inorganic N was determined after diffusion of the Kjeldahl and KCl extract, respectively (Stark and Hart 1996) and measured on an IRMS (Delta plus, Finnigan, Bremen, Germany).

Calculations and statistical analysis

The apparent N recovery (ANR) from slurry in herbage was calculated as:

$$ANR(\%) = \frac{\left(Nuptake_{slurry} - Nuptake_{control}\right)}{Napplied} \times 100 \tag{1}$$

where N=total N taken up by herbage or applied in slurry, respectively.

The percentage of slurry NH_4-^{15}N recovered in herbage (^{15}NRH) was calculated using the following equation:

$$^{15}NRH(\%) = \frac{H(c-d)}{M(a-b)} \times 100, \tag{2}$$

where H=total herbage N uptake, M=slurry NH_4-N applied, a=atom % NH_4-^{15}N of applied slurry, b= atom % NH_4-^{15}N in unlabelled slurry, c=atom % ^{15}N in herbage of labelled plots, d=atom % ^{15}N in herbage of control plots.

Similar equations apply for the NH_4-^{15}N recovery in the total soil ($^{15}NRS_T$) and in the inorganic soil N fraction ($^{15}NRS_I$). The percentage of slurry NH_4-^{15}N that was lost from the system (not recovered in herbage or soil) was calculated by difference as:

$$^{15}NLost(\%) = 100 - {}^{15}NRH(\%) - {}^{15}NRS_T(\%) \tag{3}$$

Statistical analysis was carried out using PROC MIXED in SAS. The fixed factors were application method, season of application and experimental year, including all two- and three-way interactions, and block was included as a random factor.

The calculated percentage of slurry NH_4-^{15}N lost was compared with the proportion of total ammoniacal N volatilisation predicted by the ALFAM model (Søgaard et al. 2002). The ALFAM model is based on an ammonia emission database containing data from manure application experiments conducted in eight countries representing a broad range of European climatic conditions. The emissions are described by a Michaelis-Menten-type equation. The variables significantly affecting ammonia emissions are soil moisture content, air temperature, wind speed, manure type, dry matter content and ammoniacal nitrogen content of manure, application method and application rate (Søgaard et al. 2002). The model was run with the weather and slurry composition data given in Table 1, and the measuring technique was set to micro-meteorological mass balance.

Results

Slurry composition and weather conditions

There was a large variation in slurry composition. The slurry N and particularly the ammonium content were significantly lower during summer compared to spring and the opposite was the case for the slurry DM content (Table 1). This resulted in significantly ($p<0.01$) lower NH_4-N application rates during summer compared to spring in both years (36 and 52 kg NH_4-N ha^{-1}, respectively). The mean air temperature in the 24 h after application was lower for spring than summer applications (9.5 and 12.4°C, respectively) (Table 1), whereas wind speed and radiation showed no consistent difference between spring and summer.

The weather conditions during the first cut of spring applied slurry in 2008 tended to be colder, slightly wetter and with less radiation than the same period in 2007 (Table 2).

Herbage dry matter yield

The herbage dry matter (DM) yield ranged from over 6 t ha^{-1} for the first cut after spring slurry application to less than 1 t ha^{-1} for the third cut after slurry application (Fig. 2). There was a significant ($p<0.0001$) effect of slurry application method on the yield of the first cut after slurry application, which increased in the order C < TS2 ≤ BC < TS1 (3.4, 4.3, 4.5 and 4.9 t DM ha^{-1}, respectively). During 2008, the DM yield with spring applied slurry was significantly ($p<0.001$) lower than in 2007, resulting in a significant ($p=0.002$) season × year interaction.

There was no significant effect of slurry application method on the residual yield (second and third cut (spring only) after slurry application), whereas residual yields were slightly but significantly ($p=0.003$) higher during 2007 compared to 2008 (3.2 and 3.1 t ha^{-1}, respectively) (Fig. 2).

Herbage N uptake

Similar to the DM yield, the resulting N uptake during the first cut after slurry application (Fig. 3) was significantly ($p<0.0001$) affected by application method, with N uptake increasing in the order C < BC ≤ TS2 < TS1 (53.5, 76.0, 82.1 and 85.7 kg N ha^{-1}, respectively). There was a significant ($p=0.027$) effect of application method on the residual N uptake, with the control treatment significantly lower than BC and TS1, but no significant differences between BC, TS1 and TS2 (Fig. 3). The residual N uptake was significantly ($p=0.004$) higher during 2007 than 2008 (62.0 and 50.1 kg N ha^{-1}, respectively).

The mean apparent slurry N recovery in herbage (ANR) ranged from 13 to 51% for first cut after slurry application and from 15 to 62% for the cumulative recovery within each year of application and no significant treatment effects were found (data not shown) due to the large variation (ANR ranged from −10 to 87% in the first cut after slurry application and from −76 to 108% for the cumulative cuts).

Percentage slurry NH_4-^{15}N recovery in herbage (^{15}NRH)

The ^{15}NRH averaged over all treatments and years was 26.9%, 3.4% and 0.8% for the first, second and

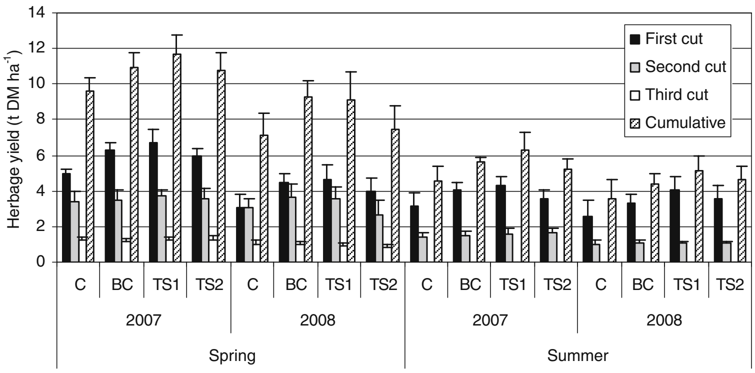

Fig. 2 The effect of slurry application method (C=no slurry applied, BC=Broadcast, TS1=trailing shoe, TS2=trailing shoe delayed by 2 weeks) and season of application (spring or summer) on the herbage dry matter yield at the first, second and third (spring only) cut after slurry application during 2007 and 2008. *Error bars*=2×SE ($n=6$)

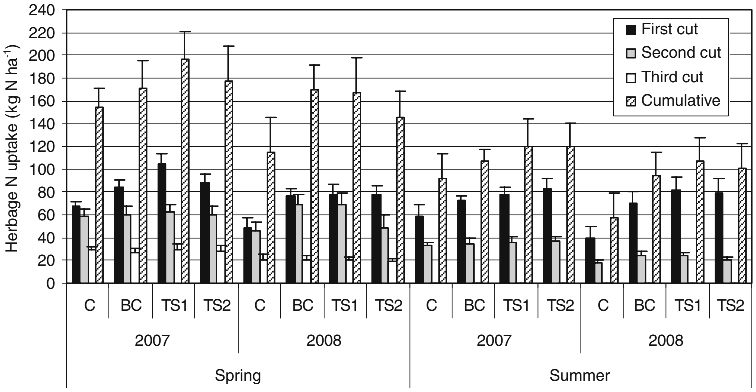

Fig. 3 The effect of slurry application method (C=no slurry applied, BC=Broadcast, TS1=trailing shoe, TS2=trailing shoe delayed by 2 weeks) and season of application (spring or summer) on the herbage N uptake at the first, second and third (spring only) cut after slurry application during 2007 and 2008. *Error bars*=2×SE (n=6)

third cut after slurry application, respectively, and the mean cumulative recovery was 31% (Table 3). There was a significant application method × season × year interaction (p=0.02) for ^{15}NRH in the first cut after slurry application. The ^{15}NRH increased in the order BC < TS1 ≤ TS2 (19.9, 28.0 and 32.4%, respectively), where TS2 was only significantly higher than TS1 for summer 2007. ^{15}NRH in the first cut after slurry application was always higher for spring compared to summer applied slurry but the difference was small and non-significant for TS1 and TS2 during 2008.

The ^{15}NRH of the residual cuts followed the same trends as for the first cut after slurry application, however, there was no significant difference between TS1 and TS2 (1.4, 1.9 and 1.9% for BC, TS1 and TS2, respectively). Additionally, the total residual ^{15}NRH was consistently and significantly (p<0.001) higher for spring compared to summer applied slurry (2.5 and 0.9%, respectively).

As a result, the cumulative ^{15}NRH was significantly affected by application method, with recoveries increasing in the order BC < TS1 < TS2 (23.2%, 32.4% and 36.7%, respectively). The only exception was for spring applied slurry, when there was no significant difference between TS1 and TS2, resulting in a significant (p=0.0092) season × application method interaction. The cumulative ^{15}NRH of spring applied slurry was significantly higher than summer applied slurry (31.4% and 26.0%, respectively), but there was a significant (p=0.0092) season × year interaction, as the cumulative ^{15}NRH of spring applied slurry during 2008 was relatively low.

Table 3 The effect of application method and timing of application on the percentage slurry NH_4-^{15}N recovered in the first, second and third cut after slurry application and cumulative cuts of herbage during 2007 and 2008. SD between parenthesis (n=6)

Harvest	Application method	2007				2008			
		Spring		Summer		Spring		Summer	
First cut	BC	27.3	(2.06)	15.6	(2.43)	24.0	(8.21)	14.5	(2.22)
	TS1	39.1	(5.52)	21.0	(2.79)	28.3	(3.69)	23.5	(3.43)
	TS2	36.7	(3.21)	34.0	(5.80)	30.0	(8.98)	27.7	(5.36)
Second cut	BC	3.7	(0.65)	2.5	(0.71)	3.2	(1.19)	1.6	(0.44)
	TS1	5.2	(0.52)	3.3	(0.63)	3.8	(1.11)	2.1	(0.45)
	TS2	5.9	(0.84)	3.3	(0.99)	3.4	(1.50)	2.3	(0.56)
Third cut	BC	0.7	(0.18)			0.5	(0.08)		
	TS1	1.0	(0.22)			0.7	(0.10)		
	TS2	1.1	(0.30)			0.8	(0.14)		
Cumulative	BC	31.7	(2.77)	18.1	(1.92)	27.7	(8.29)	18.1	(2.90)
	TS1	45.2	(5.16)	24.3	(3.18)	32.8	(3.66)	26.9	(3.99)
	TS2	43.7	(3.98)	37.3	(6.42)	34.2	(8.27)	29.9	(5.67)

Table 4 The effect of application method and timing of application on the percentage recovery of slurry NH_4-^{15}N in the soil (top 15 cm) and the percentage not recovered in soil or herbage by September during 2007 and 2008. SD between parenthesis (n=6)

	2007				2008			
	Spring		Summer		Spring		Summer	
% recovery in soil total N								
BC	24.1	(4.85)	20.3	(4.11)	21.1	(3.58)	20.9	(4.29)
TS1	31.1	(4.05)	27.5	(4.47)	36.3	(4.94)	30.6	(7.86)
TS2	30.6	(3.21)	30.4	(3.94)	35.1	(5.25)	22.5	(7.89)
% recovery in soil inorganic N								
BC	0.17	(0.06)	0.23	(0.07)	0.17	(0.10)	0.26	(0.08)
TS1	0.23	(0.06)	0.32	(0.23)	0.51	(0.10)	0.38	(0.15)
TS2	0.26	(0.06)	0.31	(0.18)	0.51	(0.10)	0.31	(0.15)
% not recovered (NLost)								
BC	44.1	(3.32)	61.7	(3.53)	51.2	(7.28)	61.1	(5.57)
TS1	23.7	(8.81)	48.2	(5.96)	30.9	(5.07)	42.5	(8.38)
TS2	25.6	(4.93)	32.3	(8.72)	30.7	(10.62)	47.6	(8.26)

Percentage slurry NH_4-^{15}N recovery in total soil N ($^{15}NRS_T$) and inorganic soil N ($^{15}NRS_I$)

$^{15}NRS_T$ at the final harvest (third and second cut for spring and summer applied slurry, respectively) was 27.5% on average (Table 4), with a significant application method × season × year interaction (p= 0.02). The $^{15}NRS_T$ was significantly lower for BC compared to TS1 and TS2 in all cases except for summer application during 2008, where there was no significant difference between BC and TS2. Similarly, there was no significant difference between TS1 and TS2, except for summer application during 2008, when TS1 was significantly higher than TS2. During 2007, there was no significant difference between spring and summer applied slurry, however, in 2008 the recovery of summer applied slurry in soil was significantly lower.

The soil inorganic N content (NO_3^- plus NH_4^+) in the top 15 cm was on average 8.8 and 16.9 mg kg^{-1} soil DM in 2007 and 2008, respectively, and there were no significant effects of application method or season of application. The $^{15}NRS_I$ was on average 0.3%, which in turn was only 1.1% of the $^{15}NRS_T$ (Table 4). There was a significant effect of application method, with BC being significantly lower than TS1 and TS2 (0.21%, 0.35% and 0.35%, respectively). There was a significant (p=0.02) season × year interaction as the %$^{15}NRS_I$ of spring applied slurry was significantly lower during 2007 than 2008.

Percentage slurry NH_4-^{15}N not recovered in soil and herbage ($^{15}NLost$)

The mean percentage of slurry NH_4-^{15}N not recovered in herbage or soil was 41.6% (Table 4 and Fig. 4). The $^{15}NLost$ was significantly (p<0.0001) higher for BC compared to TS1 and TS2 in all cases (55.1, 36.1 and 33.8%, respectively). There was no significant difference between TS1 and TS2, except for summer applied slurry in 2007, where TS1 > TS2

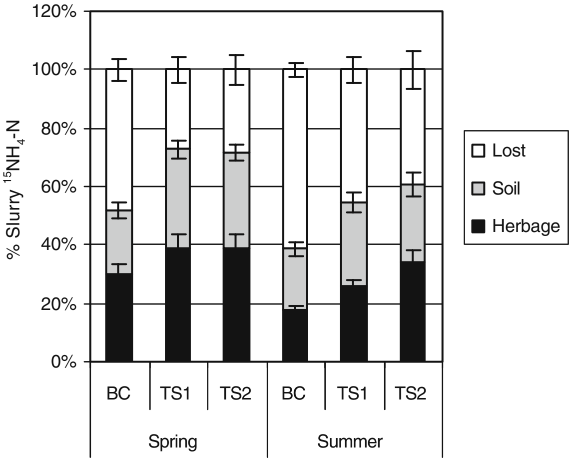

Fig. 4 Effect of application method and season of application on measured slurry NH_4-^{15}N recovery in herbage (cumulative) and in soil, and on calculated loss (all % of total applied), averaged over 2 years. *Error bars*=2×SE (n=12)

($p<0.001$). The ^{15}NLost was significantly lower for spring applied slurry in all cases except for TS2 during 2007, where there was no significant effect of application season. There was no significant difference in the ^{15}NLost between 2007 and 2008, with the exception of summer applied TS2, which was lower in 2007 compared to 2008 ($p=0.001$).

When comparing the calculated ^{15}NLost with the proportion of ammoniacal N volatilised as predicted by the ALFAM model, a strong correlation ($R^2=0.89$; $P<0.001$) was found (Fig. 5). There was no significant relative bias, but the intercept was significantly larger than zero, indicating that the ALFAM model predicted consistently higher (12% of total ammoniacal N) volatilisation than the total losses estimated in this study.

Discussion

The benefits of the use of the ^{15}N labelling method in this experiment were twofold: 1) it allowed us to calculate the recovery of slurry ammonium N in plants directly rather than by comparison with a control treatment, resulting in detectable, highly significant treatment differences and 2) it allowed us to quantify the recovery of slurry ammonium N in soil and the loss from the plant–soil system. However, some methodological issues have to be considered when interpreting the results from ^{15}N labelling studies as discussed below.

N recovery in herbage and soil—Mobilisation Immobilisation Turnover (MIT)

Due to the increased microbial activity upon slurry addition, the exchange between biomass N with the inorganic N is very rapid. This leads to a quick release of unlabelled N into the inorganic pool and microbial incorporation of ^{15}N, while the net amount of plant-available N may have remained constant (Dittert et al. 1998). When N rates applied are low relative to the amounts of soil N potentially involved in those MIT processes, recoveries based on isotope dilution tend to be in the order of 10% points lower than those based on agronomic methods (Schröder 2005a). The release of immobilised N later in the growing season is dependent on a number of factors such as C/N ratio of the manure and the soil, and nitrification activity. It is difficult to estimate these rates, since the release coincides with mineralisation processes of other slurry components (Dittert et al. 1998). In the present experiment, apparent slurry N recovery (ANR, Eq. 1) tended to be higher than the slurry NH_4-^{15}N recovered in herbage. However, the error margin of the ANR was too large to permit any meaningful comparison.

The percentage of ammonium ^{15}N recovered in soil at the final harvest in September ranged from 20 to 36%. A very small proportion of this (on average 1%) was in the form of inorganic N. This confirms that the slurry ammonium N not lost by volatilisation or taken up by the herbage was largely immobilised or fixed to soil fractions, which is in line with

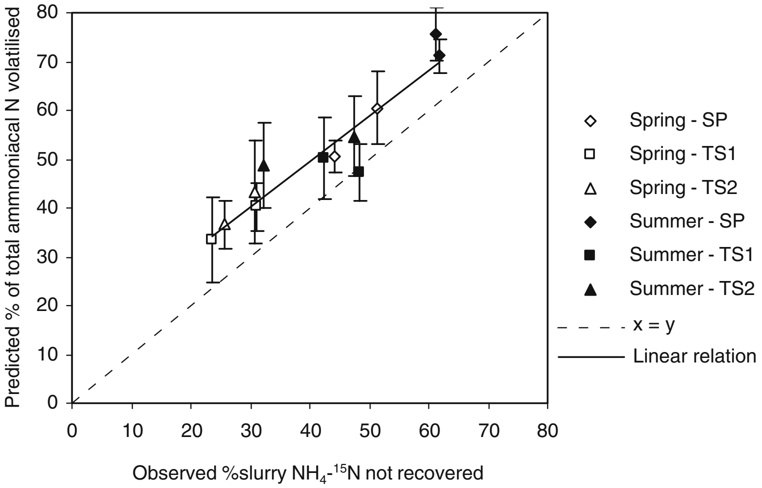

Fig. 5 Comparison of the observed slurry NH_4-^{15}N not recovered with the ammoniacal N volatilised as predicted by the ALFAM model. $p<0.0001$, $R^2=0.89$, $y=0.93\ (\pm0.23)\ x+12.1\ (\pm10.2)$, LSD in parenthesis. *Error bars*=2×SE ($n=6$)

findings from other studies (Dittert et al. 1998; Jensen et al. 2000; Morvan et al. 1997; Schröder 2005b).

The fate of lost N

The main loss pathway for slurry ammonium N in temperate regions tends to be volatilisation (Schröder 2005b), followed by losses through leaching and denitrification (Barraclough et al. 1984) and runoff. Additionally, some ^{15}N was probably incorporated into the stubble and root mass (Whitehead et al. 1990), or moved into soil layers below 15 cm, which was not accounted for in this experiment.

The ^{15}NH$_4$-N loss following application with broadcast and trailing shoe was in close agreement with values for ammonia volatilisation reported in the literature (Dowling et al. 2007; Rodhe and Rammer 2002; Smith et al. 2000). The measured ^{15}NH$_4$-N loss was consistently lower (on average 12%) than the volatilisation losses predicted by the ALFAM model. This suggests that alternative loss pathways were negligible; otherwise they would have increased ^{15}NLost closer to or even above the modelled volatilisation losses.

The effect of application method

The use of trailing shoe application significantly improved the herbage DM yield and herbage N uptake. The cumulative herbage DM yield and N uptake was on average 8% higher for TS1 compared to broadcast application. Numerous studies have compared application techniques, but the reported agronomic benefits are few, which is partly due to the fact that the differences in plant available N (as a result from differences in NH_3 volatilisation) usually equate to only a few kg per ha (Chen et al. 2001; Misselbrook et al. 1996; Smith et al. 2000). Lorenz and Steffens (1997) found significantly higher grass yield responses from trailing shoe compared to broadcast. The significant responses in the current experiment may be partly due to the low N application rate (average 100 kg Nha^{-1}, with no additional chemical fertiliser) combined with a relatively large number of replicates (*n*=6). However, efforts to analyse the ANR were not successful due to the large variability in such field experiments.

Trailing shoe application significantly improved the ^{15}N recovery of ammonium N in herbage and soil (on average by 8.6 and 10 % points, respectively) as a result of the reduction in N lost (18 % points). The main difference in recovery between TS and BC was obtained in the first cut after application, however, the recovery in the residual cuts was also significantly higher for TS.

While the increase in herbage N uptake has direct benefits from an agronomic and environmental perspective, the increase in the recovery of N in soil in September has two potential implications: 1) an increased risk of nitrate leaching and denitrification during the winter months and 2) a larger residual effect on plant growth of slurry ammonium in the subsequent year. Since only a small proportion of the recovered soil N was in the form of inorganic N, and the rate of mineralisation is relatively low in the cold and wet winter months (Gill et al. 1995), we hypothesize that benefits from residual effects (implication 2) may outweigh increased losses (implication 1).

One of the major benefits of using trailing shoe application is the larger window of opportunity for slurry spreading, because slurry can be applied at higher grass covers without negatively affecting silage quality through smearing (Lalor and Schulte 2008; Laws et al. 2002). The effect of delaying the trailing shoe application by 2 weeks was twofold: 1) The delay resulted in a shorter period between N application and harvest, which had a negative effect on the DM yield and to a lesser extent N uptake, which is in line with findings by Laws et al. (2002), and 2) the grass cover was higher at the time of TS2 application, potentially reducing ammonia volatilisation. The results suggest that the potential mitigation effect of grass cover on volatilisation is most likely to be expressed at summer time when soil and weather conditions are more conducive to volatilisation losses. It is difficult to draw firm conclusions on these factors from this experiment as the grass height effect was confounded with weather conditions during application and differences in slurry composition. For example, for summer 2008 the weather conditions were more conducive to ammonia volatilisation after TS2 application compared to TS1. Furthermore, the potentially negative effect of traffic on higher grass covers (Douglas and Crawford 1993) was not accounted for in the current experiment.

The effect of season of application

Comparison of season of application is confounded by the fact that potential plant growth and therefore N uptake is higher during spring. Additionally, the remaining growing season for grass to take up N is longer for spring (3 cuts compared to 2 cuts for summer application). However, in this experiment it is unlikely that the actual recovery in herbage was determined by this, as the N application in the form of slurry was well below the recommended fertiliser rate (Coulter and Lalor 2008). Therefore, it could be argued that in both summer and spring the herbage would take up most of the available N. Therefore, we attribute the higher recovery in both soil and herbage for spring application (4 and 10% points, respectively) to the 15% reduction in the N lost from the system.

The higher N loss during summer could be somewhat related to weather conditions after application, as average temperature and radiation tended to be higher, which may have resulted in higher volatilisation (Dowling et al. 2008). However, slurry composition was consistently different for the different application timings, with higher DM content and lower NH_4-N content during summer compared to spring, both of which tend to increase the proportion of slurry ammonium N volatilised as predicted by the ALFAM model (Søgaard et al. 2002), even though the absolute amount of NH_4-N volatilised decreases with lower slurry NH_4-N content.

The ALFAM model was used to examine the difference between spring and summer application by comparing the prediction for the spring application with the predictions for summer application based on standard summer inputs (Table 1), summer inputs with spring slurry composition and summer inputs with spring weather conditions. The results indicated that approximately 25% of the difference could be attributed to differences in weather conditions whereas the remaining 75% was the result of changes in slurry composition.

Conclusions

- The ^{15}N tracer technique is a useful tool for evaluating slurry N utilisation by perennial ryegrass swards.
- Both application season (spring versus summer) and application method (trailing shoe versus broadcast) significantly reduced the losses of slurry $^{15}NH_4$-N. These losses corresponded closely to ammonia volatilisation after application as predicted by the ALFAM model.
- The lower losses resulted in significantly higher herbage DM yields, N uptake and an increased recovery of $^{15}NH_4$-N in herbage. Additionally, the recovery of slurry $^{15}NH_4$-N in the soil (top 15 cm) at the end of the growing season was increased.
- The proportion of slurry $^{15}NH_4$-N recovered in inorganic soil N was very small compared to that recovered in the soil total N, indicating that most of the ammonium had been immobilised or fixed to soil fractions. Therefore, there is a potential residual effect of the ammonium fraction for herbage N uptake in the subsequent year and the risk of elevated losses of nitrate and nitrous oxide during the winter period is likely to be low. Further research is required to determine to what extent this residual will be available for plant growth in the subsequent year.
- Slurry N recovery in temperate pasture systems can be increased by applying slurry in spring with a trailing shoe.

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