AP42 Section:	9.2.1
Background Ch	4
Reference:	40
Title:	S.C. Jarvis, D.J. Hatch, and D.R. Lockyer, "Ammonia Fluxes from Grazed Grassland: Annual Losses from Cattle Production systems and Their Relation to Nitrogen Inputs," *Journal of Agricultural Science*, 113:99-108, 1989.

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Ammonia fluxes from grazed grassland: annual losses from cattle production systems and their relation to nitrogen inputs

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(*Revised MS received 28 February 1989*)

SUMMARY

Losses of NH_3 from a number of swards grazed by cattle were measured through 2 (1986–87) grazing years using a mass balance micrometeorological method. Comparisons were made of grass swards receiving 420 or 210 kg fertilizer N/ha per year and a grass–clover sward (GC) dependent upon fixation under rotational grazing managements. In one year a continuously grazed sward was also examined. Rates of NH_3 loss were usually greatest whilst animals were present, especially during early and late season. This was *not* always the case, however, and losses sometimes continued into the next grazing period; there were also large day-to-day variations in fluxes. Seasonal trends were also not distinct, but losses tended to be lower during early and late grazings.

The annual losses from 420 and 210 kg N/ha and GC treatments were 25, 10 and 7 kg N/ha, respectively, and the differences between treatments were still marked when losses were expressed on a per animal basis. Total loss under continuous grazing was 61% of that under the rotational system. Although the losses represent only 7·8, 5·6 and 3·7% of the inputs to 420N, 210N and GC treatments, there was a good relationship between inputs and total losses, and also between the concentration of N in the herbage and losses per animal. The effects of the measured rates of loss on the input of NH_3 from grazed grassland to the atmosphere are discussed.

25.1
9.6
6.7

INTRODUCTION

The volatilization of NH_3 results in significant and important losses of N from productive agricultural systems. Although, on a world-wide basis, there is an increasing use of urea-based fertilizers (Gould *et al.* 1986) which may result in increased NH_3 fluxes from soil plant systems, the major input of NH_3 to the atmosphere is thought to result from animal production (ApSimon *et al.* 1987; Ryden *et al.* 1987) through the return of N in excreta, especially in urine. As well as representing significant economic losses, the movement of NH_3 into the atmosphere may have important environmental consequences in influencing atmospheric chemistry (Moller & Schieferdecker 1985) and consequently in (i) increasing critical atmospheric N loads to the extent that eventual deposition changes the ecological characteristics of natural systems (Hutchinson & Viets 1969) and (ii) promoting acidification after nitrification of NH_4^+-based salts deposited on the soil (van Breemen *et al.* 1982).

Recent calculations (Ryden *et al.* 1987) and inventories (ApSimon *et al.* 1987) have indicated that losses of NH_3 from grazed grassland have a major impact on atmospheric concentrations. Because of the difficulty in monitoring losses under grazing conditions, few data exist to allow accurate assessment of these losses. Recent adaptations of micrometeorological techniques (Denmead 1983; Ryden & McNeill 1984) have, however, allowed fluxes of NH_3 to be monitored as swards are grazed. Earlier results suggested that losses frequently exceeded 1 kg N/ha per day when cattle grazed a ryegrass sward with a high fertilizer input (Ryden 1986). Furthermore, there were major differences in NH_3 losses between ryegrass swards with high fertilizer N inputs and a low input system with a grass–white clover sward dependent on N supply through fixation (Whitehead *et al.* 1986; Jarvis *et al.* 1989). Jarvis *et al.* (1989) have also related the differences in losses of NH_3 during a relatively short period in spring in each of two years, to differences in N contents in, and distributions between, faecal and urinary returns which occurred when cattle were grazing swards with differing N managements. However, there is little information on the total losses of NH_3-N from different systems over the longer term.

The mechanisms and processes involved in controlling the various equilibria which influence the distribution of NH_3/NH_4^+ between the various components of the soil system (i.e. held on the solid phase, or in aqueous or gaseous phases) and the release of NH_3 to the atmosphere are well defined (Freney *et al.* 1983). Models have been constructed which have been used to predict rates of NH_3 volatilization and the extent of losses under well-defined and constant conditions (Sherlock & Goh 1985). However, grazed swards are complex in nature with much variability and considerable interaction between the many components. Ammonia losses from swards may therefore differ from those predicted either from models or from measurements based on simple systems in field or laboratory.

In the present studies we have measured the losses of NH_3 from a number of swards which were grazed by cattle. Comparisons were made of the losses through two grazing seasons from swards receiving either high (420 kg N/ha per year), medium (210 kg N/ha per year) or zero (grass–white clover) fertilizer N input. During one of the years a comparison was also made between rotational and continuous grazing.

MATERIALS AND METHODS

Experimental site and management

Measurements of NH_3 fluxes were made during 1986 and 1987, from the same experimental swards as described previously (Jarvis *et al.* 1989) at the Institute farm at Hurley, on a freely drained loam soil (of the Frilsham series) which overlies chalk at a depth of 70–100 cm. Cattle (yearling Friesian steers of approximately 200 kg live weight at turn-out) were grazed on 0·123 ha plots (55 × 22 m) on a rotational basis, i.e. the swards were grazed for 7-day periods after which there was a 21-day recovery period before the next grazing. There were seven grazing periods between May and October; however, in 1986 two of these periods (2 and 5) were omitted because of poor sward growth. Animal numbers per treatment were determined on the basis of herbage yields which were measured by sampling the sward to 5 cm above the ground immediately before grazing started. Other conditions of sward management were as detailed previously (Jarvis *et al.* 1989).

Treatments

Three of the treatments were as described before (Jarvis *et al.* 1989), that is, ryegrass (*Lolium perenne* L.) swards receiving either 420 kg N/ha per year (420N) or 210 kg N/ha per year (210N) in seven equal dressings and at regular intervals of 28 days from mid-March, and a mixed ryegrass–white clover (*Trifolium repens* L.) sward which received no fertilizer N (GC). The swards were established in 1976 and the 420N and GC treatments had been imposed since that time. The 210N treatment was started in 1986 on an area of perennial ryegrass sward which had previously received 420 kg/N ha per year but from which the herbage had been cut and removed. In 1987 a further treatment was introduced in which a similar area of ryegrass received 420 kg N/ha per year and on which an attempt was made to maintain continuous stocking with two animals on the sward for as long as possible between May and October.

Ammonia flux measurement

Full descriptions of the principles behind and the methodology involved in the mass balance micrometeorological method for determining NH_3 fluxes from relatively small areas have been given elsewhere (Denmead 1983; Ryden & McNeill 1984). The techniques used in the present study exactly followed those described for a detailed study of losses during grazing period 2 in each of the 2 years (Jarvis *et al.* 1989). In brief, masts were placed in a central position in each of the four experimental areas. Each mast held six 100 ml sampling traps, containing 30 ml 0·002 M orthophosphoric acid, which were positioned at 0·25, 0·50, 0·75, 1·00, 1·50 and 2·00 m above the sward. Air samples were drawn continuously through the acid solution via a gas dispersion tube at 5 l/min and profiles of NH_3 concentration above each sward were established, whenever possible, for consecutive 24 h periods: these were extended to 36–48 h on a number of occasions. The NH_3 profile together with background NH_3 concentration (which was assumed to be constant with height and equivalent to the concentration at the top of the masts), the wind speed profile and wind direction at the site were then used to compute NH_3-N fluxes from each treatment in every sampling period using the same methods and parameters as before (Jarvis *et al.* 1989). Air sampling was started at the beginning of each grazing period and continued until there was no evidence of a positive flux for 3–4 days.

Throughout both years other environmental data (rainfall, maximum air temperature and potential evapotranspiration) were obtained from daily meteorological observations made at Hurley. During 1987 further measurements were made, at the experimental site, of relative humidity at sward height and soil surface temperature (using thermistor probes).

Analyses

At the end of each sampling period, the ammonia traps were replaced and the originals taken to the

Table 1. *Dates of start of grazing and animal numbers per plot* carried by swards of ryegrass receiving 420 or 210 kg N/ha per year or a grass–clover mixture receiving no fertilizer N in 1986 and 1987*

	Start date		Animal numbers					
			1986			1987		
Grazing period	1986	1987	420 kg N	210 kg N	Grass-clover	420 kg N	210 kg N	Grass-clover
1	21 Apr	7 May	←	No grazing	→	8 (65)	4 (32)	4 (32)
2	21 May	1 Jun	5 (41)	3 (24)	2 (16)	8 (65)	7 (57)	4 (32)
3	18 Jun	29 Jun	8 (65)	3 (32)	5 (41)	4 (32)	2 (16)	2 (16)
4	16 Jul	27 Jul	4 (32)	4 (32)	4 (32)	4 (32)	4 (41)	6 (49)
5	11 Aug	25 Aug	←	No grazing	→	2 (16)	2 (16)	2 (16)
6	10 Sep	21 Sep	4 (32)	4 (32)	2 (16)	4 (32)	4 (32)	3 (24)
7	8 Oct	19 Oct	3 (24)	3 (24)	2 (16)	2 (16)	2 (16)	2 (16)

* Numbers in parentheses indicate equivalent numbers of animals carried per ha.

Table 2. *Herbage yields (kg DM/ha) of swards of ryegrass receiving 420 or 210 kg N/ha per year or a grass–white clover mixture receiving no fertilizer N, prior to grazing in 1986 and 1987*

	1986			1987		
Grazing period	420 kg N	210 kg N	Grass-clover*	420 kg N	210 kg N	Grass-clover*
1	←	No grazing	→	2477	1045	1103 (24·0)
2	2327	1429	781 (16·9)	2295	2171	1132 (23·5)
3	3662	1171	1704 (19·6)	1337	601	757 (27·1)
4	1359	985	1557 (11·2)	1253	1604	1990 (35·6)
5	←	No grazing	→	688	329	475 (30·2)
6	1667	1007	767 (13·1)	492	483	432 (37·6)
7	466	624	415 (27·9)	413	366	218 (10·9)
Total (mean)	9481	5216	5224 (17·7)	8955	6599	6107 (27·0)

* Numbers in parentheses indicate proportion (%) of clover (by weight).

laboratory. The amounts of ammonia collected in each trap were determined by the phenol–hypochlorite (indophenol blue) method (Weatherburn 1967). Total N contents of herbage materials taken prior to each grazing were determined on oven-dried samples using an automated micro-Dumas method.

RESULTS

Production

Environmental/growing conditions in 1986 meant that two of the scheduled grazing periods (1 and 5) were omitted from the programme (Table 1). The average annual dry matter yields for the 2 years, as estimated by cuts taken immediately before grazing started were, for the 420N, 210N and GC treatments respectively, 9218, 5907 and 5665 kg/ha (Table 2). On average for each grazing period, this amount of dry matter supported, respectively, 39, 29 and 24 steers/ha in 1986 and 37, 30 and 26 steers/ha in 1987. These rates of stocking resulted in values of 1365, 1015, and 804 stocking days/ha, respectively, in 1986, and 1813, 1470 and 1274 in 1987. The comparable figure for the 420N continuously grazed sward in 1987 was 1431 stocking days/ha.

The proportion (by weight) of clover in the mixed swards differed considerably both between and within the 2 years. In 1986 the average content of clover (% of dry weight) was 18%, compared with 27% in 1987 (Table 2). The reasons for the increased clover content in 1987 are not clear, but the effect was consistent throughout the year.

Nitrogen in the herbage

The amount of N in the dietary intake influences the extent and form of excreted returns and hence the potential for loss through volatilization. The N

Table 3. *Nitrogen concentrations (% DM) and amounts available for consumption (kg N/ha) at the beginning of each grazing period in 1986 and 1987. Ryegrass swards received 420 or 210 kg N/ha per year and the mixed sward received no fertilizer N*

Grazing period	1986 420 kg N %	1986 420 kg N kg/ha	1986 210 kg N %	1986 210 kg N kg/ha	1986 Grass–clover %*	1986 Grass–clover kg/ha*	1987 420 kg N %	1987 420 kg N kg/ha	1987 210 kg N %	1987 210 kg N kg/ha	1987 Grass–clover %*	1987 Grass–clover kg/ha*
1	← No grazing →						3·34	82·7	2·72	28·4	3·19 2·49 4·38	35·2 20·9 11·6
2	3·64	84·7	2·85	40·7	2·70 2·40 4·28	21·1 15·6 5·7	3·70	84·9	2·55	55·4	3·11 2·69 4·11	35·2 23·4 10·9
3	2·56	93·7	2·92	34·2	2·21 1·87 3·26	37·7 25·6 10·9	4·23	56·5	3·17	19·0	2·94 2·61 3·87	22·2 14·4 7·9
4	2·87	39·0	2·15	21·2	1·54 1·28 3·41	24·0 17·7 6·0	3·82	47·9	3·18	51·0	2·57 2·12 3·45	51·1 27·2 24·4
5	← No grazing →						4·16	28·6	3·40	11·2	3·37 3·11 4·38	16·0 10·3 6·3
6	3·94	65·7	2·96	29·8	2·76 2·72 3·77	21·2 18·1 4·8	4·38	21·5	3·82	18·5	3·85 3·27 4·79	16·6 8·8 7·8
7	4·32	20·1	3·70	23·1	3·29 2·21 3·86	13·7 8·4 5·3	4·30	17·7	3·59	13·1	2·96 2·75 4·36	6·5 5·3 1·0
Mean/total	3·47	303·2	2·92	149·0	2·50 2·21 3·86	117·7 85·8 32·7	3·99	339·8	3·20	196·6	3·14 2·72 4·19	191·8 121·3 69·1

* Values for mixed sward show overall figure for herbage, followed by data for separated grass (upper value) and clover (lower value).

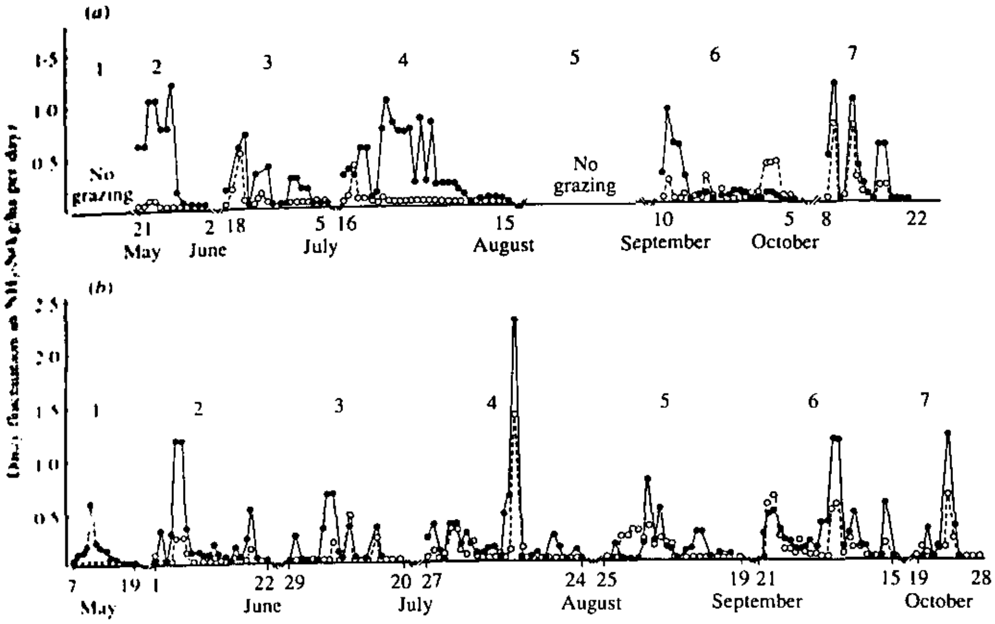

Fig. 1. Daily fluctuation in NH_3-loss (kg N/ha per day) from swards during and after seven 1-week grazings by yearling steers in (*a*) 1986 and (*b*) 1987. Losses from a ryegrass sward receiving 420 kg fertilizer N/ha per year (●——●) and from a mixed grass clover sward receiving no fertilizer N (O---O) are shown.

concentrations in the herbage were always greater in the 420N treatment (on average, 3·47 and 3·99%, in 1986 and 1987, respectively) than in either of the other two treatments (Table 3). In both years the overall concentration in the herbage from the mixed sward was only slightly lower than that in the 210N treatment. The average total amounts for the grazing season that were available for consumption (as assessed by cuts prior to grazing) were, respectively, [illegible], 173 and 155 kg N/ha for 420N, 210N and GC treatments.

NH_3 losses: treatment and seasonal effects

Although only data for the 420N and GC treatments are shown in Fig. 1, the trends in the daily fluctuations were similar in all treatments; the daily losses from 210N and GC swards were not as great as from 420N. As found in previous studies (Ryden 1986; Jarvis *et al.* 1989), the rates of NH_3 loss were usually greatest whilst the animals were present on the swards (Fig. 1) especially in early and late season; there were considerable fluctuations in the daily rates of loss which on occasion were as high as 2·5 kg/ha per day. Although in some grazing periods fluxes stopped promptly with the removal of the animals, in others significant losses continued for many days after the animals had been removed, sometimes until the following grazing period. In both years the length of the period during which losses were detected tended to be shorter during early and late grazings. Table 4 shows a summary of environmental data for each period of measurement during 1987 and indicates that it is difficult to isolate individual environmental factors as influencing day-to-day variation and overall loss. The lowest losses during grazings 1 and 7 were coincident with cool periods with low potential evapotranspiration, but there is no obvious reason for the high rate and extended period of loss in grazing 7.

In the first year, the total loss of NH_3-N over each grazing period was always lower from the GC sward than from the 210N grass (Fig. 2): the distinction in the second year between these two treatments was not as clear. In both years, the total loss was always greater from the high-N input (420N) treatment than from the other two treatments.

Whilst seasonal trends were not very distinct, the losses of NH_3 tended to be lower during early and late grazing periods than at other times of the year. The maximum overall rate of loss occurred during grazing 4 (i.e. during August) in both years, when over 8 kg N/ha were lost in 1986 and over 6 kg N/ha in 1987, from the 420N treatment. The 420N ryegrass sward carried considerably more animals (Table 1) than the other two rotationally grazed treatments and it might have been presumed that this higher density was entirely responsible for the greater rate of NH_3 loss from this treatment. However, even when losses are

Table 4. *Ranges and mean values for environmental factors over periods of NH_3 flux measurement from grazed swards in 1987*

Grazing period	Days of measurement*	Wind speed† (m/sec)		Air temperature max (°C)		Soil surface temperature (°C)		Relative humidity (%)		Rainfall (mm)	Potential evapotranspiration (mm)
		Range	Mean	Range	Mean	Range	Mean	Range	Mean		
1	13 (11)	1·20–5·14	3·26	11·7–21·1	13·9	10·8–15·2	12·9	—	—	29·8	25·3
2	22 (19)	1·40–6·35	2·48	12·2–19·2	16·3	12·8–19·4	15·7	40–100	68	55·6	39·5
3	22 (19)	1·32–5·20	2·42	16·6–27·6	22·2	16·3–23·3	21·1	64–100	76	30·5	7·2
4	29 (25)	1·15–5·74	2·53	17·2–27·6	21·3	16·3–22·8	19·2	55–94	80	31·8	61·1
5	22 (19)	1·10–4·61	2·64	16·0–24·4	19·4	14·0–20·1	16·9	78–100	83	23·8	29·9
6	23 (20)	0·87–5·30	2·70	11·0–21·6	15·1	11·2–18·0	13·7	63–100	83	31·2	23·9
7	12 (11)	1·12–3·01	1·77	11·5–16·7	13·3	8·4–12·7	10·4	84–100	94	36·7	5·2

* Numbers in parentheses indicate number of samplings.
† At 2 m above sward.

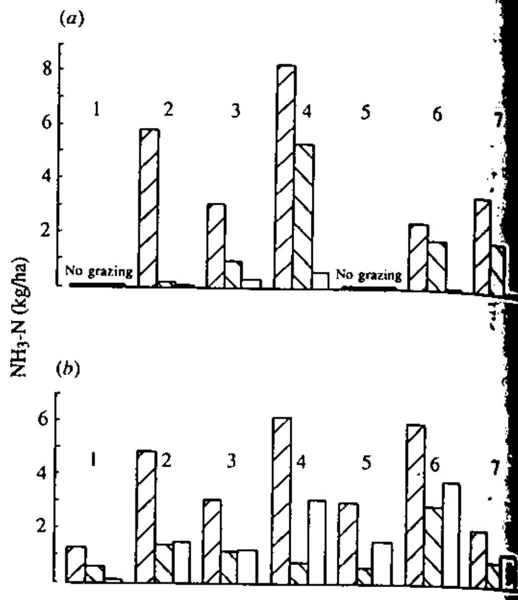

Fig. 2. NH_3-N losses (kg/ha) from swards during and after seven 1-week grazings by yearling steers in (*a*) 1986 and (*b*) 1987. Swards were either ryegrass receiving 420 (▨) or 210 (▧) kg fertilizer N/ha per year, or grass–clover (□) receiving no fertilizer N.

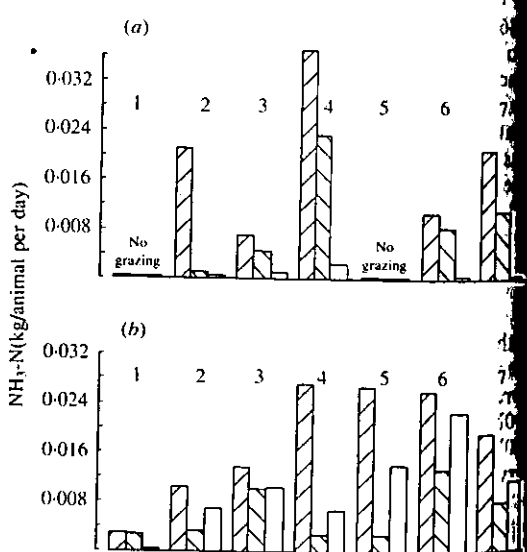

Fig. 3. NH_3-N losses from yearling steers (kg/animal) in (*a*) 1986 and (*b*) 1987. Swards were either ryegrass receiving 420 (▨) or 210 (▧) kg fertilizer N/ha per year, or grass–clover (□) receiving no fertilizer N.

Table 5. *Summary of losses of NH_3-N from grazed swards of ryegrass receiving 420 or 210 kg N/ha per year and a mixed grass–clover sward receiving no fertilizer N*

	1986			1987			
				420 kg N			
NH_3-N losses	420 kg N	210 kg N	Grass-clover	Rotational	Continuous	210 kg N	Grass-clover
Total (kg N/ha per year)	23·5	10·5	1·0	26·7	16·3	8·6	12·5
Loss per animal (kg N/animal per day)	0·019	0·010	0·001	0·018	0·011	0·007	0·010
Proportion (%) of fertilizer or fixed* N input lost as NH_3	5·6	5·0	0·6	6·4	3·9	4·0	9·0
Proportion (%) of dietary N available for consumption	7·7	7·0	0·9	7·9	—	4·2	6·5

* Assumes 160 kg N/ha per year acquired through fixation (Whitehead *et al.* 1986).

expressed on a per animal basis (Fig. 3) the distinctions between the treatments are still obvious and the losses per animal per day from 420N, 210N and GC treatments were in the ratio 21:11:1 in 1986 and 2:1:1 in 1987. The relative losses between 420N and 210N were therefore similar and the major variability in the amounts lost between years occurred with the GC sward.

The annual total losses were, on average for the 2 years, 25·1, 9·6 and 6·7 kg/N ha (Table 5) from the 420N, 210N and GC rotationally grazed treatments. Because of the restricted size of the plots, it was impossible to maintain animals throughout the year on the 420N continuously grazed treatment and stocking days/ha were therefore lower than with the 420N rotational treatment (i.e. 1431 and 1813, respectively). Total NH_3 losses from the continuous system were only 61% of those from the rotational system. In all of the treatments the total amounts lost therefore represent relatively low proportions of the N input to the system, whether as fertilizer or as biologically fixed N (Table 5), as well as low proportions of the amounts of N taken up into the standing crop and available for consumption by the cattle. Despite the low losses, there is a good relationship between the inputs of N and amounts lost (Fig. 4) whether expressed on a per unit area or per animal basis.

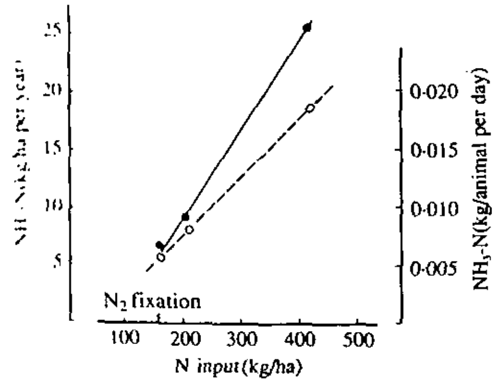

Fig. 4. Relationship between fertilizer N or N_2 fixation input and annual NH_3-N losses per unit area (●——●) or daily losses per animal (○---○).

DISCUSSION

Losses of NH_3 as measured by the mass balance method represent a net loss, since there may be significant flows of NH_3 from the atmosphere to the sward, and absorption from soil and atmospheric sources by actively growing foliage (Lockyer & Whitehead 1986) (see Fig. 5).

Models exist which have been constructed to describe the physical and chemical conditions which are influential in their impact on (i) the enzymic hydrolysis of urea and subsequently (ii) the various equilibria which control the distribution of NH_3 gas and NH_4^+ ions between solid, solution and gaseous phases (see Fig. 5). From a chemical standpoint, NH_3 volatilization will largely be determined by pH (i.e. by alkalinity) and ammoniacal N content, and their combined effects can be considered the 'NH_3-volatilization potential' (Vlek & Craswell 1981). Actual loss rates from the soil surface will then be

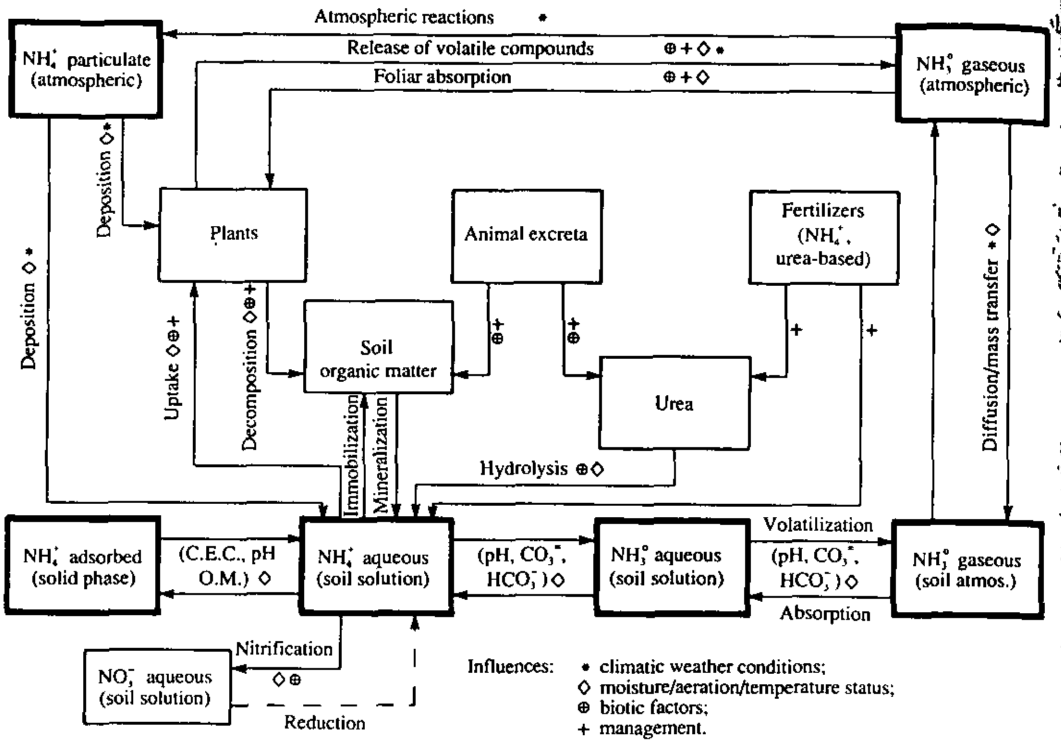

Fig. 5. Schematic representation of the origin and fate of ammonia in grassland systems.

determined by environmental factors (Fig. 5). Wind speed has been demonstrated to be particularly important for losses from flooded paddy fields (Vlek & Craswell 1981). Their diffusion model indicates that, with low wind speeds, diffusion rates are very small and the gas phase dominates; with increasing wind speed the volatilization rate increases and the liquid phase resistance becomes more significant because of depletion of NH_3 in the surface film of the liquid phase (see Fig. 5). The grazed sward embraces a complex set of conditions with many interactions between the various components of the soil/plant/animal pathway which may influence NH_3 equilibria and which may be further confounded by environmental factors. Predicting the behaviour of NH_3/NH_4^+ and the extent of loss from grazed swards may therefore be difficult.

In the present studies, whilst the total amounts of measured NH_3 lost did not differ greatly between the 2 years, and there were some seasonal trends, there was considerable variation both between grazing periods and from day-to-day, the causes of which were not obvious. In our earlier study (Jarvis *et al.* 1989), the largest determinant in the removal of NH_3 appeared to be wind speed as indicated by Vlek & Craswell (1981). A detailed assessment of the contribution of the measured environmental variables to NH_3 loss will be given elsewhere (D. J. Hatch, S. C. Jarvis & G. Dollard, unpublished).

The relationship obtained between N input and total loss is of some significance and indicates that, as far as NH_3 loss is concerned, it is total N input and not the form, which is of importance. There was considerable similarity between the total amounts lost in the 2 years from the same treatments with fertilizer N. The losses from the mixed sward were more variable but this might have been expected because the clover component, and hence N fixation, varied both within and between the 2 years. The relationships obtained assume that the amounts acquired through fixation by the mixed sward over the 2 years of measurement were similar to those estimated in previous studies (Whitehead *et al.* 1986), i.e. 160 kg N/ha.

Whether originating from fertilizer or from fixation, it is clear that the overall N concentration in the diet is of importance in determining loss. If two exceptional sets of data are omitted from the analysis, there is a strong positive relationship between the N concentration (% in the dry matter) of the herbage at the onset of a grazing period (x) and the amount of NH_3-N (kg/animal per day) lost during that period (y). For treatments under rotational management and in both years (34 observations)

$$[illegible] -0.0202 + 0.0091x \quad (r = 0.734, P < 0.001).$$

The N concentration in the diet affects both the total amounts of N in excreta and distribution between dung and urine (Jarvis *et al.* 1989). Although some NH_3 may be lost from dung, urine has by far the greatest potential for loss (Ryden *et al.* 1987). If it is assumed that all the N in the herbage prior to grazing was available for intake, then, on average, this amount is equivalent to 77 and 82% of the fertilizer N applied to 420N and 210N grass swards, respectively, and [illegible] of the N estimated to have been acquired through fixation in the mixed sward (Whitehead *et al.* 1986). Making further assumptions that (i) the proportions of the ingested N that were excreted were [illegible] and 79% and (ii) 74, 60 and 56% of the excreted N was in urine, from 420N, 210N and GC treatments, respectively (Jarvis *et al.* 1989), potentially, 207, 81 and 69 kg N/ha could have been returned to the respective swards as urine.

Most other studies of NH_3 loss have been based on measurements of losses from urine applied to small plots. In one case, 66% of the N applied in this way was lost in warm dry conditions, but only 6–16% during cooler or wet weather (Ball 1982). Other estimates range between 14–28% of applied urine N in Queensland (Vallis *et al.* 1982) and 9–25% from the urine in the UK (Ryden *et al.* 1987). In contrast, NH_3 loss by volatilization from urine patches in a short grass prairie with moderate stocking rates (Schimel *et al.* 1986) was not an important loss mechanism for N and was an order of magnitude lower than originally suggested (Woodmansee 1978), the measured range being between 0·01 and 0·08 g [illegible] per year. Repeating the previous assumptions, it can be calculated that the mean annual losses of NH_3 represent 12·1, 11·2 and 9·8% of the urinary N returned in 420N, 210N and GC swards, i.e. well within but at the lower end of. the ranges previously reported. Denmead *et al.* (1974) estimated higher losses of NH_3 produced at the base of lucerne swards in Australia, but later showed that a large proportion of this was re-absorbed (Denmead *et al.* 1976). The pattern of grazing and its impact on canopy structure therefore have important implications for NH_3 loss from grassland. It is of interest to note that losses per animal from the 420N continuously grazed treatment were less than 70% of those with rotational grazing. In this instance, any benefit derived through increased absorption by the taller sward during the initial stages of the grazing in the rotation system were outweighed by greater cattle stocking density and excretal returns and increasing pressure on the various equilibria shown in Fig. 5. Furthermore, the much reduced sward height at the end of rotational grazing (i.e. a reduced boundary layer) may also result in increased NH_3 exchange near the base of the sward where NH_3 is produced.

Patterns of loss under grazing are often considerably different from those from urine-treated plots where the loss of NH_3 is largely complete within 7 days of treatment (Ryden 1984). Thus, intermittent losses of varying extents occur in the field for considerable periods after the animals are removed. This may indicate that other sources (i.e. from faeces and senescing vegetation) are contributing to the net NH_3 loss and provide an explanation for the variable nature of the fluxes.

As well as the possible economic significance of losses of NH_3, the potentially adverse effects on the environment have also been highlighted recently (ApSimon *et al.* 1987). Our data indicate that the emission quotient (i.e. the ratio of NH_3-N lost to that N available for loss) from grazed pastures is considerably lower than previously suggested (ApSimon *et al.* 1987). Assuming that (*i*) 370 t N/year are excreted on British grassland (Ryden *et al.* 1987), (ii) on average, N fertilizer application to grassland is of the order of 200 kg/ha per year, (iii) the NH_3-N emission rate from urine is 11%, and that for dung is 3% (Ryden *et al.* 1987) and (iv) the ratio of excreted N in dung to N in urine when 200 kg N/ha are applied is 1:1·5 (Jarvis *et al.* 1989), the overall emission quotient for NH_3 from excreted N under grazing conditions is approximately 8% rather than the suggested figure of 15% (Ryden *et al.* 1987). This reduces total annual UK NH_3-N loss from grazed pastures from 55 to 29·6 t, which is equivalent to approximately 9% of the estimated total NH_3-N loss from UK grassland and livestock production (Ryden *et al.* 1987).

Other assessments of the contribution of grazed grassland to NH_3 fluxes to the atmosphere have been based on census data (ApSimon *et al.* 1987), and losses estimated on a per capita basis. Our data indicate that not only must animal numbers be taken into consideration, but also the quality of their diets with respect to N contents. Both variables will be determined to a large extent by inputs of N either through fertilizer addition or N_2 fixation. It should also be emphasized that the present results relate to a single soil type. Other physical and chemical conditions may result in different equilibria in other soil types. Furthermore, losses of NH_3 may also depend upon animal breed, and species, and the age of the animal. Further information is required to define precisely a 'global' figure for NH_3 loss from animal production to the wider environment, both during grazing and from animal housing.

We are grateful to D. H. Roberts and S. E. Reynolds for technical assistance and to C. Craig for help in maintenance of the experimental plots. The work was commissioned by the Ministry of Agriculture, Fisheries and Food, London.

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