Ammonia volatilization from grazed pastures

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SUMMARY

During the grazing seasons of 1986 and 1987, the ammonia volatilization from urine patches was measured in 24 experiments on sandy soil, clay soil and peat soil. The experimental and environmental conditions were varied during the season. A wind tunnel system was used in which the climatic conditions were nearly equal to the ambient conditions. Artificial urine with a N content of 6 to 12 g l^{-1} was applied at a rate of 5 l m^{-2}. Ammonia volatilization was measured up to 10 days after urine application in 1986 and up to 30 days after application in 1987. At an urine N application rate equivalent to 600 kg ha^{-1} the ammonia N emission varied between 6 and 19 % (mean 13 %) of the urine N applied. About 80 % of the ammonia emission occured during the first 4 days after urine application. No significant differences in volatilization between experiments on sandy, peat and clay soil were observed. The total ammonia emission was not predominantly influenced by a single climatic factor, except rain which caused a lower emission. Volatilization also decreased with lower N concentrations in the urine.

On the average 30 % of the nitrogen applied in urine patches on sandy soil was not accounted for at the end of the experimental period. This budget loss was even higher on clay and peat soil. The N budget loss was absent in experiments in which the plots were treated with the nitrification inhibitor dicyandiamide (DCD).

In addition the ammonia volatilization from dung pats and decaying grass was measured. The ammonium N content of the dung pats volatilized conpletely, corresponding with 13 % of the N applied with the manure (1250 kg ha^{-1}). Approximately 3 % of the N in decaying grass leaves volatilized as ammonia.

Using the ammonia emission factor of 13 % for urine patches and dung pats, the total ammonia emission from grazed pastures at 3 levels of N fertilization was calculated. During a 180-day grazing period the ammonia emission amounts to 45 kg N ha^{-1} at an N fertilization level of 390 kg ha^{-1}, and to 35 kg N ha^{-1} at an N fertilization level of 310 kg ha^{-1}.

SAMENVATTING

Tijdens het weideseizoen van 1986 en van 1987 werd onder verschillende experimentele- en omgevingsomstandigheden de ammoniakvervluchtiging uit urineplekken gemeten. Voor de metingen werd een windtunnelsysteem gebruikt, waarin de milieu-omstandigheden vrijwel gelijk waren aan de omgevingsomstandigheden (buiten de tunnel). Kunsturine, met een N-gehalte van 6-12 g l^{-1}, werd toegediend in hoeveelheden van 5 l m^{-2}. De ammoniakvervluchtiging werd in 1986 tot 10 dagen en in 1987 tot 30 dagen na urinetoediening gemeten. Bij een urine-N gift van 600 kg ha^{-1} varieerde de ammoniak-N emissie tussen 6 en 19 % (gemiddeld 13 %) van de toegediende urine-N. Circa 80 % van de ammoniakemissie trad op tijdens de eerste vier dagen na urinetoediening. Er werden geen significante verschillen in vervluchtiging waargenomen tussen experimenten op zand-, klei- en veengrond. De totale ammoniakemissie werd niet overwegend door één enkele milieufactor bepaald. Alleen door regen werd de vervluchtiging verlaagd. De ammoniakvervluchtiging nam eveneens af met een lagere N-concentratie in de urine.

Gemiddeld 30 % van de in een urineplek op zandgrond toegediende N werd aan het eind van het experiment niet teruggevonden in de bodem, als gewasopname of als ammoniakvervluchtiging. Op klei- en veengrond was dit N-balansverlies nog hoger. Het N-belansverlies was afwezig in experimenten waarin de proefveldjes met de nitrificatieremmer dicyaandiamide (DCD) waren behandeld.

De ammoniakvervluchtiging van mestplekken en van rottend gras werd eveneens gemeten. De ammonium-N uit de mestplekken vervluchtigde volledig, overeenkomend met 13 % van de met de mest toegediende N (1250 kg ha^{-1}). Circa 3 % van de N uit het rottende gras vervluchtigde als ammoniak.

Gebruikmakend van de ammoniakemissie-factor van 13 % voor urine- en mestplekken werd de totale ammoniakemissie uit beweid grasland bij drie N-bemestingsniveaus berekend. Tijdens een weideperiode van 180 dagen bedraagt de ammoniakemissie 45 kg N ha^{-1} bij een N-bemestingsniveau van 390 kg ha^{-1} en 35 kg N ha^{-1} bij een N-bemestingsniveau van 310 kg ha^{-1}.

1. INTRODUCTION

In intensively managed grassland with a N input of 400 kg $ha^{-1}yr^{-1}$ about 85 % of the N ingested by the cattle is excreted in the urine and dung (Van Vuuren and Meijs, 1987). The corresponding deposition of urine N is 260 kg ha^{-1}(180 $days)^{-1}$ in patches of 600 kg ha^{-1}. Several authors mention ammonia losses from 6 to 60 % of the urine N voided (Ryden, 1986, Sherlock, 1984, Vallis, 1982, Ball, 1984). As a consequence, the ammonia volatilization from urine patches could be equivalent to 150 kg N ha^{-1}(180 $days)^{-1}$. At that volatilization level, a large fraction of the total ammonia emission in the Netherlands, estimated at 230.10^{6} kg N per yr would originate from the one million hectare of grassland. Therefore the relation between nitrogen fertilization level, environmental conditions and the ammonia volatilization from urine patches was studied. The work was part of the Dutch Priority Programme on Acidification.

Ammonia-free air was ventilated through transparent tunnels placed over experimental urine and dung plots in grassland. The experiments were carried out with artificially prepared urine to prevent inconveniences of working with decaying urine. From the ammonia volatilization of single urine patches the ammonia emission from grazed grassland at different levels of nitrogen fertilization was calculated.

2. MATERIAL AND METHODS

Experiments were carried out in 1986 and 1987 on grassland on a sandy soil at the experimental farm "Droevendaal" at Wageningen. Some experiments were situated on grassland sown on a peat soil and a clay soil. For this purpose the upper soil layer of suitable grassland soils was dug off and deposited in 5 m * 2 m * 0.5 m pits near the institute. Soil characteristics of the three soil types are summarized in Table 1.

Table 1. Soil characteristics

Soil type	pH-KCl	Organic matter (%)	$CaCO_3$ (%)	Clay fraction (%)	CEC me(100 g)$^{-1}$	Cationic composition % of CEC			
						Ca	Mg	K	Na
Sandy soil	5.0	5.7	n.d.	n.d.	16.3	33.9	4.4	0.8	0
Clay soil	7.4	2.6	6.4	28	21.2	n.d.	5.4	0.8	0
Peat soil	5.7	71.6	n.d.	n.d.	130.0	18.8	2.0	0.3	0

The experimental plots were fertilized with ammonium nitrate limestone at a level of 140 or 480 kg N ha^{-1}yr^{-1} in 1986 and of about 400 kg N ha^{-1}yr^{-1} in 1987. The grass was cut at weekly intervals during the season. Nitrogen was applied at 3-weekly intervals but not after application of urine. The last cutting was not less than 5 days before starting an experiment. Urine was sprayed evenly over plots of 2 m * 0.55 m at an application rate of 5.0 l m^{-2} in most experiments. In each experiment three plots were prepared. Two plots were treated identically, over one of these plots the measuring tunnel was placed. The third plot was used as a blanc, no urine was applied. Artificial urine was prepared according to Doak (1952), the composition is given in Table 2. Urine with a lower N content was prepared by dilution.

Table 2. Composition of artificial urine with a total-N content of 12.2 g l^{-1}

Compound	Concentration, g l^{-1}	N as % of total N
Urea	24.0	89.1
Hippuric acid	10.0	6.2
Creatinine	0.200	0.6
Allantoin	0.500	1.4
Uric acid	0.070	0.2
Ammonium chloride	1.20	2.5
		100.0
$KHCO_3$	19.2	
KCL	14.3	

Manure was applied evenly over the plot at 32 kg m^{-2} immediately after collection from grazing cows. The composition of the manure, used in experiment 13, is given in Table 3.

Table 3. Composition of manure in experiments 13.1 and 13.2

Dry matter	Total N	NH_4^+-N	NO_3^--N	K	P	Organic matter	pH
g kg^{-1} fresh weight						g kg^{-1} dm	
138	3.92	0.29	0.018	1.37	1.01	788	6.0

The experimental plot was covered by a clear polycarbonate tunnel, 2 m * 0.55 m * 0.6 m, mounted on an iron frame to a depth of 12 cm in the soil to avoid leakage at the soil surface. Ammonia-free filtered air was blown through the tunnel by a centrifugal fan at airspeeds of 0.5, 1.0 or 1.5 m s^{-1}, that is 600, 1200 or 1800 m^3 h^{-1}. The air was filtered through a polypropylene airconditioning filter, with an filter area of 3.6 m^2, that was impregnated with phosphoric acid.

The air flow rate through the tunnel was measured with a turbine gas meter. The outflowing air was sampled with a membrane pump drawing the air at 5-13 l min^{-1} through a gas-washing bottle filled with 0.3 M phosphoric acid. The sample volume was determined with a domestic gas meter. The ammonia captured in the phosphoric acid solution was analyzed with an automated continuous flow analysis system based on the Berthelot reaction.

The N detection limit of the method is 0.001 kg $ha^{-1}hr^{-1}$, corresponding with an atmospheric NH_3 concentration of 0.1 µg m^{-3} with a sampling period of 24 hours and an airspeed of 1.0 m s^{-1}.

The gas-washing bottles were replaced every 4 h during the first 4 days after urine application. During the night period (20^h-8^h) one sample was taken. From the fourth day the gas-washing bottles were replaced at 8 A.M. and 8 P.M. At that time the surface pH of the soil and the temperature of the top soil layer, to a depth of 3 cm, were measured in the experimental plots under the tunnels and in the uncovered parallel plots. The efficiency of the ammoniafilter was determined by sampling the air directly after passing the filter. The filter efficiency gradually decreased from 98 % to 80 %. At an ammonia background concentration of 10 µg m^{-3} and an airspeed in the tunnel of 1 m s^{-1} the corresponding correction for the ammonia volatilization amounts to 0.04 to 0.4 kg $ha^{-1}day^{-1}$. The soil surface pH was measured directly with a flat-surface

combined pH electrode after moistening the soil with deionized water. The temperature of the top soil was measured with thermocouples.
At the start and at the end of the experimental period the ammonium and nitrate content of a soil to a depth of 40 cm were determined in the experimental, the parallel and the control plots. Soil moisture content was determined simultaneously.
Solar radiation data were obtained from the nearby meteorological station of the Agricultural University Wageningen. At the end of the experiment, generally 3 weeks after urine application, the grass was harvested and analyzed for nitrogen content.
The nitrogen budget for the experiment was calculated from data on urine application, ammonium and nitrate content of the soil, nitrogen uptake by the grass and ammonia volatilization.

3. EXPERIMENTS

During the grazing seasons of 1986 and 1987 28 experiments on ammonia emission were carried out. In each experiment the ammonia volatilization from urine patches, or from dung or decaying grass, was continuously measured over a period of at least 10 days. In each experimental period two experiments were run simultaneously under slightly different experimental conditions. In this way the effect of environmental factors on the ammonia volatilization was studied. The experimental conditions for the experiments on ammonia volatilization after urine application are summarized in Tables 4 and 5. The conditions in the experiments with dung and decaying grass are summarized in Table 6. During the 1986 experiments the air speed in the tunnel was 1.5 $m\ s^{-1}$ during the day and 0.5 $m\ s^{-1}$ during the night. In 1987 the air speed was 1.0 $m\ s^{-1}$, day and night. A short description of the experiments is given below.

3.1. Experiments with urine on sandy soils

Experiments 1

Ammonia volatilization at different urine N concentrations and application rates.

Nitrogen fertilization level 140 kg $ha^{-1} yr^{-1}$.

Urine application 5 $l\ m^{-2}$, nitrogen contents 6 and 12 $g\ l^{-1}$.

Experiments 2

As experiment 1.

Nitrogen fertilization level 480 kg $ha^{-1} yr^{-1}$.

Experiments 3

Effect of rain on ammonia volatilization. Nitrogen fertilization level 140 kg $ha^{-1}\ yr^{-1}$.

Urine application 5 $l\ m^{-2}$, 12 g N l^{-1}.

Exp. 3.1.: 12 l water m^{-2} was sprayed over the experimental plot immediately after urine application.

Exp. 3.2.: 12 l water m^{-2} was sprayed over the plot in 4 daily portions of 3 $l\ m^{-2}$ each, the first immediately after urine application.

Experiments 4

Effect of rain on ammonia volatilization.

Nitrogen fertilization level 480 kg $ha^{-1}yr^{-1}$.

Urine application 5 l m^{-2}, N content 12 g l^{-1}.

Exp. 4.1.: No extra water was added.

Exp. 4.2.: 12 l water m^{-2} was sprayed over the urine patch immediately after urine application.

Experiments 5

Effect of sward length on ammonia volatilization.

Nitrogen fertilization level 140 kg $ha^{-1}yr^{-1}$.

Urine application 5 l m^{-2}, 12 g N l^{-1}.

Exp. 5.1.: Prior to the urine application the sward was cut to the ground-level, learing stubbles of 2 cm length.

Exp. 5.2.: The urine was applied to a sward which had been mown 1 week before. The sward was 8-10 cm.

Experiments 6

Ammonia volatilization at two nitrogen fertilization levels. Repeats experiments 1.2 and 2.2 under summer conditions.

Nitrogen fertilization level 140 and 480 kg $ha^{-1}yr^{-1}$.

Experiments 7

Effect of air speed on ammonia volatilization.

Nitrogen fertilization level: 480 kg $ha^{-1}yr^{-1}$.

Urine application 5 l m^{-2}, 12 g N l^{-1}.

In order to maintain a high pH and a high ammonium concentration, nitrification was inhibited by the addition of dicyandiamide (DCD). DCD was applied at 20 kg ha^{-1}, 4 days before the start of the experiment and 40 kg ha^{-1} with the urine.

Experiments 14

Ammonia volatilization at two rates of urine application.

Nitrogen fertilization level: 360 kg $ha^{-1}yr^{-1}$.

Exp. 14.1: Urine application 3.3 l m^{-2}, 9 g N l^{-1}.

Exp. 14.2: Urine application 10 l m^{-2}, 9 g N l^{-1}.

Experiments 15

Effect of pH on ammonia volatilization, as exp. 7.
Nitrogen fertilization level 360 kg $ha^{-1}yr^{-1}$.
Urine application 5 l m^{-2}, 12 g N l^{-1}.
Exp. 15.2: DCD was applied as in exp. 7.
In exp. 15.1 no DCD was applied.

3.2. Experiments with urine on clay soil and peat soil

Experiments 8, 9 and 11

Ammonia volatilization from urine patches on clay and peat soil. In these experiments the ammonia volatilization in an experiment on clay soil was compared with a experiment on peat soil. No control plots were established.
Nitrogen fertilization level 400 kg $ha^{-1}yr^{-1}$.
Urine application, 5 l m^{-2}, 12 g N l^{-1}.

3.3. Experiments with decaying grass and dung

Experiments 12

Ammonia volatilization from decaying grass. 2 Kg freshly cut grass from a highly fertilized meadow was spread over the 1.1 m^2 plot, and moved to the soil surface by hand action. The grass was wetted every morning by spraying with 5.5 l of water per m^2. Experiments 12.1 and 12.2 were exact duplicates. Ammonia volatilization was recorded over a 12 day period. At the end of the experimental period the grass residues were collected and analyzed.

Experiments 13

Ammonia volatilization from dung pats. 35 kg of freshly collected manure from grazing cows was spread over the 1.1 m^2 experimental plot.
Exp. 13.1: Daily the manure was wetted at 8 and 16 hour with 3 liter of water.
Exp. 13.2: No water was added.

4. RESULTS

In this section the effects of experimental and environmental factors on ammonia volatilization will be discussed.

4.1. Ammonia volatilization from urine patches

4.1.1. General characteristics of the ammonia volatilization

A typical emission and pH curve is presented in Figure 1 for the results of experiment 15.1. The ammonia volatilization is expressed in kg N per hectare urine patch.

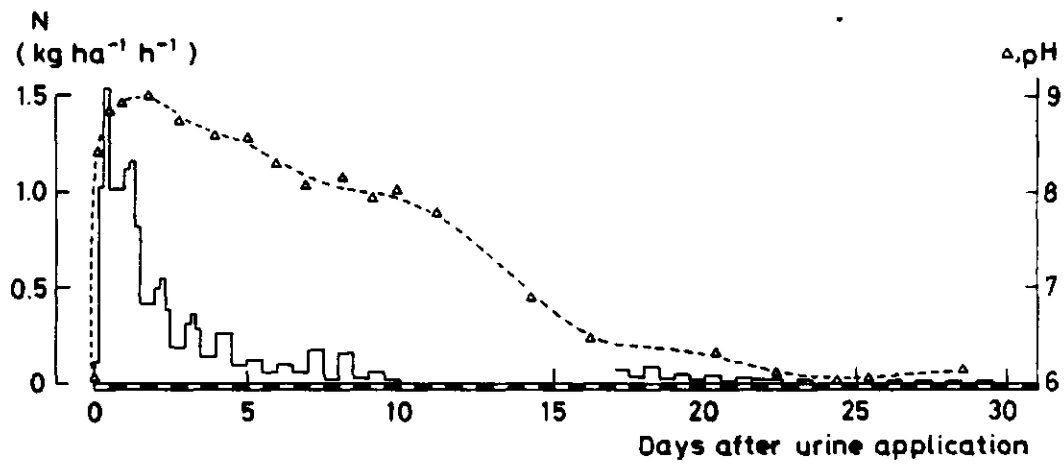

Figure 1. Rate of ammonia volatilization, kg N $ha^{-1}h^{-1}$ and soil surface pH following urine application in experiment 15.1

Within a few hours after urine application the ammonia volatilization rate increases to a maximum level of about 1.5 kg N $ha^{-1}h^{-1}$, followed by a rapid decrease of volatilization. At night the volatilization rate is 1/2 to 1/7 times of that during the day as a result of lower radiation.

The amount of ammonia volatilized in 10 days corresponds to approximately 10% of the urine N applied. About 70 % of the ammonia emission in this period occurs during the first three days after urine application. Total emissions were calculated by assuming that the daily emission gradually decreases from the 10^{th} day level to zero at day 30 for the 1986 experiments or by interpolation in the extended experiments for the 1987 experiments.
The initial soil surface pH is 6.0. The pH increases to about 9 within a few hours after urine application, and decreases rather rapidly during the next days. The initial pH is restored after one month. At that time nitrification is

4.1.2. Effect of air speed, radiation and temperature on volatilization

Data on ammonia volatilization in twelve-hour periods for the experiments with urine are summarized in Tables 7 and 8 for the initial 10 days and in Table 9 for the extended periods. The ammonia volatilization rate was higher during the day than during the night. In the 1986 experiments this effect of radiation and temperature was increased by a higher air speed during the day. By day the air speed in the tunnel was adjusted to 1.5 m s^{-1}, in accordance with average outside weather conditions. The air speed at night was lowered to 0.5 m s^{-1}. In the 1987 experiments the air speed was kept constant, day and night, at 1.0 m s^{-1}.

The direct effect of air speed and radiation on volatilization is difficult to determine as the volatilization decreases with time and the radiation changed rapidly during the day.

From the volatilization data in Tables 7 and 8 the ratio between the emission in a day period and the emission in the next night period, or the ratio of the emission in a day period and the emission in the preceeding night period can be calculated.

During the night transport of ammonium to the top soil layer decreased by lack of evaporation and upward water transport. Probably as a result of ammonia depletion in the top soil and a consequent decrease of nightly emissions, the ratio between daily and nightly emissions gradually increased.

In the 1986 experiments the mean value of the day/night emission ratio was two times higher than in the 1987 experiments. This effect is a result of the relatively low nightly air speed in 1986: a threefold increase in air speed resulted in a twofold increase in emission. However, the total emission did not increase in 1987.

The relative increase in ammonia emission could be calculated from the emission data of experiment 7. In this experiment the air speed in the tunnels was changed frequently from 0.5 to 1.5 m s^{-1} and reverse in such a way that the two installations continuously operated at different airspeeds. From this the relative increase in volatilization for a threefold increase in airspeed was calculated. The relative increase in ammonia volatilization gradually decreased during the day, probably as a result of ammonia depletion in the top soil layer (Figure 2). The upward transport of ammonium was insufficient to maintain the ammonia volatilization at the same level, especially during periods with higher air speed.

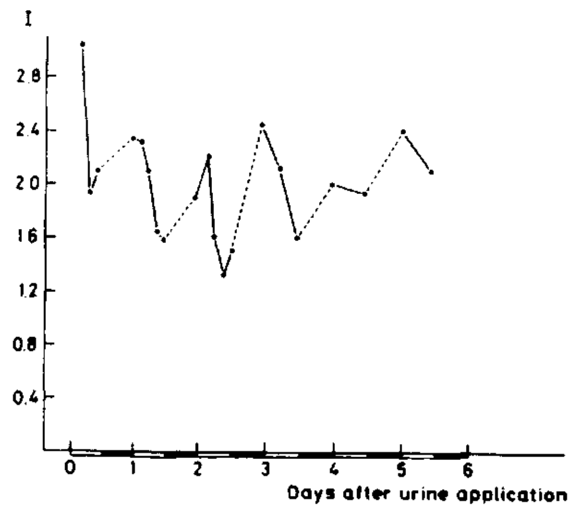

Figure 2. Relative increase in ammonia volatilization (I) after alteration of the airspeed from 0.5 to 1.5 m s^{-1}. Data from experiment 7.

Soil temperature depends highly on the global radiation. Temperature effects of the daily variation in irradiation are restricted to about 5 °C on sandy soils covered by grass under Dutch climatic conditions with high soil moisture contents (Tables 4, 5). Radiation energy is the most important factor, stimulating water evaporation and ammonia volatilization. However no correlation was observed between global radiation and ammonia volatilization in 10 days (Figure 3).

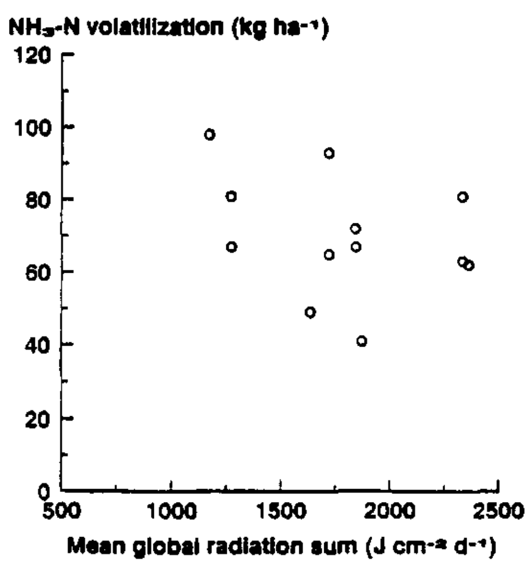

Figure 3. Total ammonia volatilization, kg N ha^{-1}(10 days)$^{-1}$ vs. mean global radiation sum. Objects with 600 kg urine N per ha on sandy soil,

Only the results of experiments on sandy soils at an urine N application level of 600 kg ha^{-1} are considered. Experiments with an additional rain application are also omitted.
Indirect effects of irradiance are possible via higher soil temperatures and lower soil moisture contents.
In Figure 4, the ammonia volatilization per xperiment is plotted against the mean temperature of the upper soil layer at 16 P.M. Again the graph is restricted to experiments on sandy soils with 600 kg urine N applied and no additional water application. No predominant effect of temperature on total ammonia emission can be observed.

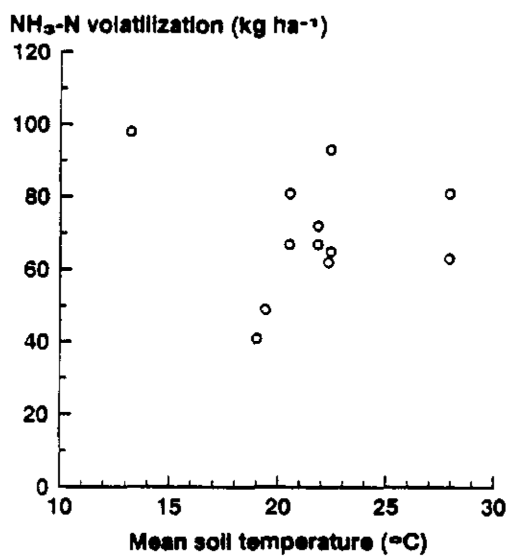

Figure 4. Total ammonia volatilization, kg N ha^{-1}(10 days)$^{-1}$ vs. mean temperature at 0-3 cm soil depth at 16 P.M. Objects with 600 kg urine N per ha on sandy soil, rain application excluded.

4.1.3. Relation between initial soil moisture content and ammonia volatilization

The sandy soil of the experimental farm gradually dried during the summer of 1986. The initial soil moisture content for all experiments is given in table 4. In Figure 5 the total ammonia volatilization per experiment is plotted against the initial soil moisture content. Like in the foregoing section only the results of the experiments on sandy soil with an urine N application level of 600 kg ha^{-1} are plotted. Experiments 3.1 and 4.2 are omitted. No significant effect of the soil moisture content on the total ammonia volatilization could be observed.

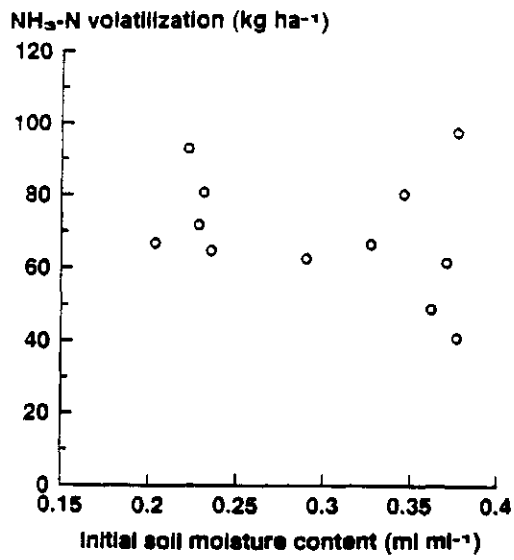

Figure 5. Total ammonia volatilization, kg N $ha^{-1}(10\ days)^{-1}$ vs. initial soil moisture content. Objects with 600 kg urine N per ha on sandy soil, rain application excluded.

4.1.4. Effect of the urine N concentration on volatilization

In practice, the nitrogen concentration in urine ranges from 6 to 15 g l^{-1} (Lantinga, 1987). The ammonia volatilization was lower than expected (Ryden, 1986). To improve the accuracy in most experiments urine with relatively high N-concentrations was used. In 2 experiments on sandy soil with an urine N concentration of 6 g l^{-1} and an application rate of approximately 300 kg ha^{-1} (experiments 1.1 and 2.1) the mean ammonia emission in 10 days was 25 kg N per ha urine patch (Table 4).
The average ammonia emission of the other 14 experiments on sandy soil, with 12 g N per l urine and a rate of application of 600 kg N ha^{-1}, was 70 kg N ha^{-1} (Table 4). With a higher nitrogen concentration in the urine, a progressive increase in the ammonia volatilization was observed. It could be concluded from experiments 14 and 15 (Table 5) that the ammonia emission depends more on the N concentration in the urine, than on the volume of urine applied. This conclusion is supported by the results of experiments 3.1 and 4.2 in which the urine patch was sprayed with water. The ammonia emission was reduced considerably after the treatment with water (Table 4).

In Figure 6 the total ammonia volatilization for the experiments on sandy soil is plotted against the N concentration in the urine applied. The objects to which an additional amount of rain was applied, are omitted from the graph. The ammonia emission is significantly enhanced with higher urine N concentra-

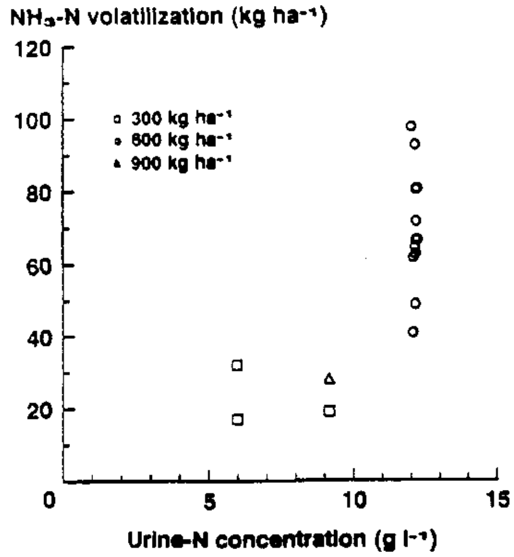

Figure 6. Total ammonia volatilization, kg N ha^{-1}(10 days)$^{-1}$ vs. N concentration in urine objects on sandy soil, rain application excluded.

Little information is available about the relation between feed composition and the volume and N concentration of the excreted urine. In our experiments the urine N concentration was rather high. Consequently the ammonia emission as calculated from the experiments is a high estimate of the situation in the field.

4.1.5. Relation between nitrogen fertilization level and ammonia volatilization

No direct effect was measured of the N status of the sward and the soil on the ammonia emission from urine patches (Table 4). Under practical conditions a lower N-fertilization level results in a decreased grass production and N content in the herbage and reduction of the excretion of urine N per hectare.

4.1.6. Relation between soil surface pH and ammonia volatilization

Daily values of the soil surface pH are tabulated in Table 10. After urine application, the soil surface pH rapidly rises to pH 9. The next two or three days the soil pH is only slightly affected by the relatively low ammonia emission. Then pH decreases, probably as a result of nitrification: the pH and the volatilization remain high after addition of a nitrification inhibitor (exp. 7.1, 7.2, 15.2). The initial pH is restored after one month. During that period only 13% (4-17%) of the urine N applied has been emitted as ammonia.

Neither in the beginning, nor at the end of the experimental period a predictive equation for the ammonia volatilization from pH data could be computed from the results in Table 7, 9 and 10.

4.1.7. Ammonia volatilization from urine patches on different soils

No significant differences in ammonia emission were measured from urine patches on a sandy soil, a peat soil and a clay soil with widely different physicochemical characteristics (Table 4) The ammonia emission was not influenced by the soil type.

4.1.8. Nitrogen budget of urine patches

The N-budgets of the urine patches have been calculated at the end of the experiments from the amount of urine N applied, the final amount of urine N that has been left as ammonium N and nitrate N in the soil, the N uptake in the grass and the ammonia N volatilization. The soil N and grass N uptake values are corrected with the corresponding values of the control plots. For all experiments N budgets are calculated and summarized in Tables 11 and 12. The budgets are calculated over 10-day periods in 1986 and over monthly periods in 1987. For the 10 objects on sandy soil (1.2 to 6.2) where approximately 600 kg urine N per ha was applied, an average N budget loss of 190 kg ha^{-1} has been calculated. Such a high N-budget loss did not occur in plots with a low nitrification level (experiments 5.2, 7.1, 7.2 and 15.2) neither in the plots with a low rate of application of urine N (experiments 1.1, 2.1 and 4.1). It is hypothesized that the N loss is the result of a chemodenitrification process at high ammonia concentrations. Considerably higher N losses have been observed in the experiments on clay and peat soils.

4.2. Characteristics of the ammonia volatilization from dung pats

Ammonia volatilization from dung was measured from an artificial dung pat of 2 m * 0.55 m to which 32 kg m^{-2} freshly collected manure has been applied, giving a total N application of 1250 kg ha^{-1} (Tables 3, 6). The ammonium N content, analyzed by the continuous flow method, was 2.1 g per kg dry matter. An additional content of ammonia producing nitrogen compounds, approximately 1 g per kg dry matter, is not determined by this method (Van Faassen, 1987).
The ammonia emission from a repeatedly wetted dung pat was 128 kg N ha^{-1} in 12 days (Table 6). The emission from a dry dung pat was 117 kg ha^{-1}. The total ammonia N emission in 29 days was 181 kg ha^{-1} in experiment 13.1 and 148 kg

ha^{-1} in experiment 13.2. This total emission was calculated from the measured emissions in the 12-day period and the extended period. The general characteristics of the ammonia volatilization from dung pats (Figure 7) are different from those of urine patches with respect to the range of the diurnal variation in volatilization and retarded ammonia emission (Figure 1). The diurnal temperature variation was 15 °C. The total ammonia N emission amounts to 13% of the total nitrogen content of manure. This emission factor equals the ammonia emission factor for urine patches.

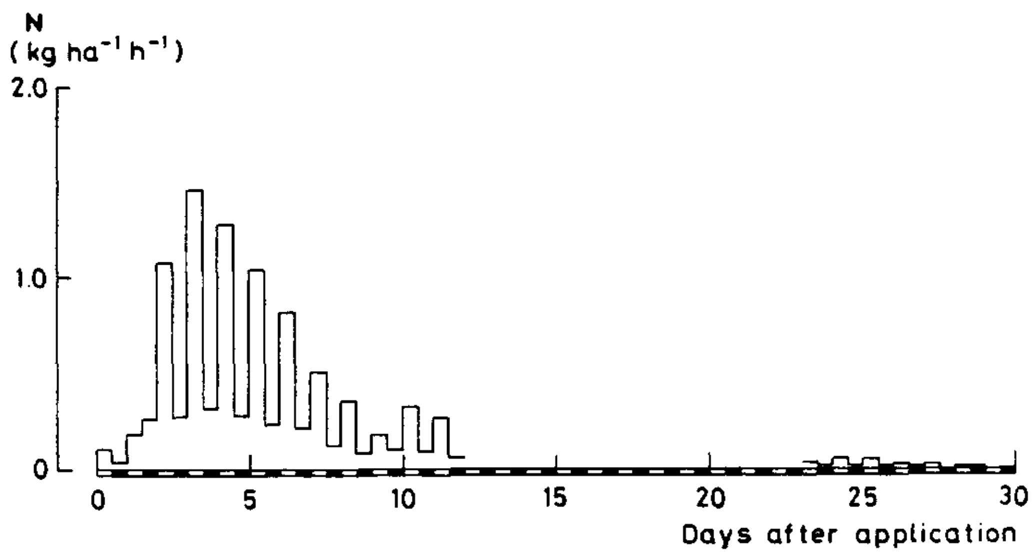

Figure 7. Rate of ammonia volatilization, kg N $ha^{-1}h^{-1}$ following manure application in experiment 13.2.

4.3. Ammonia volatilization from decaying grass leaves

A relatively large amount of fresh grass (18000 kg ha^{-1}, 2700 kg dry matter ha^{-1}) was distributed over the experimental plot (exp. 12, Table 6). The grass was sprayed with 5.5 mm of water, once a day during the experimental period. The measured ammonia N emission was about 3 kg ha^{-1} in the 12-day period. After this period only 33% of the grass could be recovered, with a similar N content as the applied grass. At an estimated grazing loss of 400 kg dry matter ha^{-1} per grazing cycle, the ammonia volatilization from grass residues can be estimated to be 3 kg ha^{-1}(180 days)$^{-1}$.

4.4. Ammonia volatilization from untreated grass swards

In 1987 the ammonia emission from grass swards on sandy-, clay- and peat soils was determined before urine application. Results are shown in Table 13.
In 12 experiments on sandy soils N volatilization rates varied between -0.12 and 0.07 kg $ha^{-1}(24\ h)^{-1}$, the mean value was -0.06 kg N $ha^{-1}(24\ h)^{-1}$. A negative value implies absorption of ammonia by the grass sward. The absorption could be measured because of the presence of residual ammonia in the filtered air.
The average value of the ammonia emission from untreated grass swards can be considered as the detection limit of the total measuring system. The so determined detection limit is approximately 10 kg N $ha^{-1}(180\ days)^{-1}$. The detection limit of the method of analysis is approximately 4 kg N $ha^{-1}(180\ days)^{-1}$.

4.5. Level of the ammonia emission in extended periods

In the 1986 experiments the ammonia volatilization rate was measured until 10 days after urine application. At the end of that period N volatilization rates varied between 0.0 and 4.9 kg $ha^{-1}(24\ h)^{-1}$, (Table 4). For calculation of the total ammonia emission from a urine patch it was assumed that the 10^{th} day emission level linearly decreased to zero in the next 20 days. Under this assumption the emission in the period from 10 to 30 days after urine application was calculated by multiplying the 10^{th} day emission value by a factor 10.
In 1987 the ammonia volatilization in the period from about 25 to 30 days after the urine (or dung) application has been actually determined. The results are compiled in the Tables 5 and 9. The above mentioned assumption that the 10^{th} day emission level decreases to zero in the period from 10 to 30 days after urine application was justified by the experimental results. Only in the experiments 15.2 and 11.2 the ammonia volatilization rate remained at a level higher than 0.1 kg N $ha^{-1}(24\ h)^{-1}$. In exp. 15.2 nitrification was inhibited, resulting in a high ammonium content of the soil (Table 12) and a relatively high soil surface pH (Table 10) at the end of the experimental period. This explains the higher ammonia volatilization rate (in experiment 15.2) than in exp. 15.1.

4.6. Effect of the wind tunnel system on ammonia emission

The question may arise to what extent different climatic conditions under the tunnel may have influenced ammonia volatilization.
Mean values of the temperature of the upper soil layer, the soil surface pH and the soil moisture content are given in Table 14 for tunnel-covered and for uncovered plots.
The average inside temperature of the soil inside the tunnel was 1.5 °C higher than the average soil temperature outside. No significant differences in soil surface pH have been observed. At the end of the experimental period the soil moisture content inside the tunnel was 0.045 ml ml^{-1} lower than in the outside plots.
During experiments 14 and 15 a substantial rainfall was measured. The final soil inorganic N content of the tunnel covered plots was, averaged over all experiments, equal to the soil inorganic-N contents of the outside plots. For single experiments the difference between inside and outside soil N contents was occasionally high, due to irregular distribution of inorganic N over the soil profile and a consequent lack of sampling accuracy (Table 15). Only in experiments 14 and 15, in which the outside plots were exposed to heavy rainfall, the final soil nitrogen contents under the tunnel were somewhat higher than in the adjacent plots. As the inside and outside final soil inorganic nitrogen contents are almost equal, the ammonia volatilization was not noticeably influenced by the tunnel canopy.

5. DISCUSSION

5.1. Ammonia volatilization from urine patches

The ammonia volatilization from urine patches measured in our experiments was on the average 13 % of the applied urine N. 30 Days after application the ammonia volatilization rate had decreased to zero. The ammonia volatilization loss was low compared with values reported in literature on the subject (see below). Analytical errors and deviations from ambient climatic conditions were minimized in the wind tunnel system that was used in the experiments.

To avoid interference from high atmospheric ammonia concentrations, the ventilation air was filtered ammonia-free. The detection limit of the system was 0.02 kg N $ha^{-1} day^{-1}$. The air speed in the tunnel, 0.5 to 1.5 m s^{-1} was sufficiently high to avoid excessive temperature increase by solar irradiation. The volume of the ventilation air was directly measured with a turbine gas meter.

By comparison the air speed was low in the enclosure methods used by Ball (1979) and Sherlock (1984), 0.01 m s^{-1} and 0.05 m s^{-1} respectively. The relatively high volatilization rates reported by the authors mentioned, 28 % and 20 % over 7-day periods, could be explained by high temperatures in the enclosures during the day. Vallis (1982) reported ammonia volatilization losses of 14 to 28 % over a 14-day period. These results were obtained after correction for back diffusion of ammonia. The recovery was only 48 %. In addition, the measuring period was frequently interrupted during removal of the cover. Ryden (1982) reported nitrogen losses by ammonia volatilization, calculated as 35 to 53 % of the amount of fertilizer N applied. The ammonia emission corresponds with 50 to 80 % of the urine N excreted in a 28-day period. However, these results were obtained with an aerodynamic method and not in a "closed" system.

A slightly higher ammonia volatilization could be expected in a wind tunnel system in comparison with the outside emission due to a higher soil temperature and a lower soil moisture content under the tunnel canopy. The effect of these differences was only small. The final soil inorganic N content of the tunnel-covered plots was, averaged over all experiments, equal to the soil inorganic N contents of the outside plots. For single experiments the difference between inside and outside soil N contents was occasionally high, due to irregular distribution on inorganic N over the soil profile and a consequent lack of sampling accuracy.

Artificial urine was used throughout the experiments. The hydrolysis rate of urea in artificial urine equals the urea hydrolysis rate in cattle urine if the artificial urine contains hippuric acid (Doak, 1952). No significant differences in ammonia volatilization between plots treated with artificial urine and plots treated with sheep urine were observed (Sherlock and Goh, 1984) The urine application rates used in our experiments, 300 to 600 kg N ha^{-1} were in the range of usual application rates mentioned in the literature (Ball, 1979, Sherlock, 1984, Vallis, 1982).

The ammonia volatilization rate increased with higher irradiation, temperature, air speed and a lower soil moisture content. The total ammonia emission was relatively low and not markedly influenced by these environmental factors. It may be concluded that a large fraction of the initial ammonia emission originates from urine adhering to the leaf and litter layer of the sward. This conclusion is supported by the observation that the magnitude of the ammonia volatilization was related to the N concentration of the urine. At higher urine N concentrations and corresponding lower volumes of the voided urine, a larger fraction of the urine adheres to the leaf and litter layer. These observations are supported by the results of experiments 3.1 and 4.2, in which the ammonia volatilization decreased after spraying of the urine patch with water, simulating heavy rainfall.

A substantial fraction, on the average 30 %, of the nitrogen applied in urine patches on sandy soil was not accounted for at the end of the measuring period. This budget loss was even higher on clay and peat soil (Table 11, 12). The lost N was not temporarily immobilized. The N loss increased slightly during the season. The N budget loss was absent in experiments in which the plots were treated with the nitrification inhibitor dicyandiamide (DCD). The N loss coincided with a high nitrification level. The N loss seems to be the result of a chemodenitrification process. Similar N budget losses were reported by Ball (1979) and Vallis (1982).

Due to the infiltration of a large part of the urine into the soil, only a small fraction of the urine N volatilizes as ammonia. Dung pats lie on the soil surface. The labile ammonium fraction of the manure, comprising 13 % of the total nitrogen content of the manure, volatilizes as ammonia. Consequently, during grazing 13 % of the N excreted in urine and dung volatilizes as ammonia.

5.2. Effect of N fertilization level on ammonia emission from grazed pastures

During grazing urine, with a N concentration of 6 to 14 g l^{-1} is voided in patches of about 0.4 m^2. At the end of the grazing season about 25% of the grassland area is covered with urine patches and 5% of the area is covered with dung pats. It was concluded in section 5.1 that 13% of the amount of nitrogen excreted with urine and dung volatilizes as NH_3. The urine-N and dung-N excretion depends on the grass uptake which in turn depends on the grass yield and N-fertilization level. The ammonia emission has been calculated for three types of grassland farms. Relevant technical information about these farm types has been derived from literature (Van der Meer, 1983; Biewinga et al., 1987).

Farm type 1

Intensive grassland farms like the Nitrogen Pilot Farms (Van der Meer, 1983) or the specialized dairy farms included in a survey of the Research Institute for Agricultural Economics (data cited by Biewinga et al., 1987). On these farms the average rate of fertilizer N on grassland and fodder crops is 320-380 kg $ha^{-1} yr^{-1}$. Fodder crops, mainly silage maize, occupy slightly over 10 % of the land. The nitrogen content of grass at grazing stage is 44 g per kg dry matter. The average livestock density is 3.5 cattle units per ha (1 cattle unit has the same feed intake as a cow with an annual production of 4000 kg fat corrected milk, viz. 14 kg dry matter per day). The amount of purchased feeds is about 2000 kg dry matter per cattle unit per year. The output of N in milk and sold animals in 84 kg $ha^{-1} yr^{-1}$.

Farm type 2

Grassland farms with an economical use of fertilizer N, viz. 240-275 kg $ha^{-1} yr^{-1}$. This rate is based on an analysis of the relationship between the rate of fertilizer N and dry matter yield in N manuring experiments which suggested that the level of fertilizer N at Farm type 1 is excessive (CABO, Annual Report 1986, pp. 34-41). Livestock density and production on Farm type 2 equal those on Farm type 1. The nitrogen content in the grass at grazing stage is 35 g per kg dry matter.

Farm type 3

Grassland farms without fertilizer N. Nitrogen is supplied by biological fixation and purchased feeds. An example of this farm type is the farm of Mr. Cuperus in Friesland (Van der Meer, 1983). Livestock density on this farm is 1.85 cattle units per ha. The amount of purchased feeds is only 470 kg dry matter per cattle unit. The output of N in animal products is 38 kg $ha^{-1} yr^{-1}$. The N content in the grass at grazing stage is 30 g per kg dry matter.

For ease of calculation it was assumed that

- the production of milk and liveweight is equally distributed over the year;
- the animals remain 24 hours per day at pasture during the grazing season of 180 days;
- the animals consume only fresh grass during the grazing season;
- for each farm type volatilization of ammonia is 13 % of N voided in urine and dung.

The results of the calculations are summarized in Table 16.

Table 16. Ammonia volatilization from grazed pastures on 3 dairy farm types in the 180 days of the grazing season.

	Farm type		
	1	2	3
Cow-grazing days: days ha^{-1}	630	630	333
N-uptake with ration kg ha^{-1}	390	310	140
N in product kg ha^{-1}	42	42	19
N in urine and dung kg ha^{-1}	348	268	121
NH_3-N volatilization kg ha^{-1}	45	35	16

With a careful fertilization procedure, as practised in farm type 2, it is possible to reduce the ammonia emission to 75% of the emission of the high N-input farm type 1, without affecting the production level. Farm type 2 represents the average practice in the Netherlands in 1986.
In farming systems without N-fertilization (farm type 3) the ammonia emission can be further reduced to 50% of the emission in farm type 2. However, under these conditions both the livestock density and the milk production per hectare are reduced with 50 % as well.

6. CONCLUSION

Ammonia volatilization from urine patches was relatively low and ranged from 6 to 19 % (mean 13 %) of the urine N applied. The major part of this ammonia volatilized within 4 days after application. The rate of volatilization was highly influenced by environmental conditions: irradiation, soil temperature and wind speed. However, the total ammonia emission in a monthly period was not clearly related to varying climatic factors, except rain. In addition the volatilization was reduced at lower urine N concentrations. Obviously, a large part of the ammonia emission originates from urine adhering to the leaf and litter layer of the sward. After adsorption of ammonium to the mineral soil, and consecutive nitrification, the ammonia volatilization is negligible.
A substantial fraction (30 %) of the nitrogen applied in urine patches on sandy soils was not accounted for at the end of the experiment. This budget loss was even higher on clay and peat soils. A large part of the urine N was probably lost by denitrification.
The ammonia emission from grazed pastures depends on the yield and the nitrogen content of the grass. As the ammonia emission from dung pats was also 13 %, the ammonia volatilization from grazed pastures in the Netherlands could be calculated. The emission during a season (180 days) is equivalent to 35 kg N per hectare. The additional amount of ammonia volatilization from decaying grass leaves has been estimated at 3 kg N per ha.

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Table 4. Experimental conditions and ammonia volatilization during the 10-day periods of the experiments in 1986 and 1987.

No. exp.	Period	N-fertilization level	Urine-N applied	NH_3-N-volatilization In period	In last 24 hours	Mean global radiation sum	Mean temperature (°C) of the soil layer 0-3 cm		Initial soil moisture content of the layer 0-10 cm
		kg $ha^{-1}year^{-1}$	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	J $cm^{-2}day^{-1}$	at 8.00 AM	at 4.00 PM	ml ml^{-1}
Sandy soil									
1.1	21/04-01/05 '86	140	284	32	1.4	1169	10.3	13.2	0.384
2.1	12/05-22/05 '86	480	285	17	0.5	1869	14.2	19.0	0.356
1.2	21/04-01/05 '86	140	565	98	2.8	1169	10.3	13.2	0.377
2.2	12/05-22/05 '86	480	566	41	0.1	1869	14.2	19.0	0.377
3.1	26/05-04/06 '86	140	607	23	0.8	1631	14.2	19.4	0.346
3.2	26/05-04/06 '86	140	607	49	0.4	1631	14.2	19.4	0.362
4.1	09/06-19/06 '86	480	604	62	0.3	2361	17.5	22.3	0.371
4.2	09/06-19/06 '86	480	604	42	0.1	2361	17.5	22.3	0.352
5.1	23/06-03/07 '86	140	609	63	4.0	2332	20.8	27.9	0.290
5.2	23/06-03/07 '86	140	609	81	2.9	2332	20.8	27.9	0.231
6.1	07/07-17/07 '86	140	610	67	1.9	1840	17.7	21.8	0.203
6.2	07/07-17/07 '86	480	610	72	1.7	1840	17.7	21.8	0.228
7.1	04/08-14/08 '86	480	607	65	3.3	1716	17.7	22.4	0.235
7.2	04/08-14/08 '86	480	607	93	4.9	1716	17.7	22.4	0.222
14.1	14/07-24/07 '87	360	303	19	0.5	1511	19.2	23.7	0.188
14.2	14/07-24/07 '87	360	918	28	0.4	1511	19.2	23.7	0.185
15.1	03/08-13/08 '87	360	610	67	0.9	1270	15.9	20.5	0.327
15.2	03/08-13/08 '87	360	610	81	2.0	1270	15.9	20.5	0.346
Clay soil									
8.1	22/09-02/10 '86	400	598	30	0.6	873	12.9	18.0	0.315
9.1	06/10-16/10 '86	400	607	27	0.9	659	14.5	17.6	0.329
11.1	27/04-06/05 '87	420	601	21	0.3	1454	12.5	17.4	0.272
Peat soil									
8.2	22/09-02/10 '86	400	598	35	1.3	873	13.4	19.3	0.553
9.2	06/10-16/10 '86	400	607	76	2.6	659	15.4	18.6	0.461
11.2	27/04-06/05 '87	420	601	10	0.3	1454	13.4	19.1	0.477

Table 5. Experimental conditions and ammonia volatilization during the 10-day periods and the extended periods (ext.) of the experiments in 1987.

No. exp.	Period 1987	N-fertilization level	Urine-N applied	$N\text{-}NH_3$-volatilization In period	$N\text{-}NH_3$-volatilization In last 24 hours	Mean global radiation sum	Mean temperature (°C) of the soil layer 0-3 cm		Initial soil moisture content of the layer 0-10 cm
		$kg\ ha^{-1} year^{-1}$	$kg\ ha^{-1}$	$kg\ ha^{-1}$	$kg\ ha^{-1}$	$J\ cm^{-2} day^{-1}$	at 8.00 AM	at 4.00 PM	$ml\ ml^{-1}$
Sandy soil									
14.1	14/7-24/7	360	303	19	0.5	1511	19.2	23.7	0.188
14.1 ext.	13/8-20/8			0.6	0.0	1318	18.3	21.1	n.d.
14.2	14/7-24/7	360	918	28	0.4	1511	19.2	23.7	0.185
14.2 ext.	13/8-20/8			1.0	0.0	1318	18.3	21.1	n.d.
15.1	03/8-13/8	360	610	67	0.9	1270	15.9	20.5	0.327
15.1 ext.	20/8-03/9			4.7	0.1	1120	18.0	21.7	n.d.
15.2	03/8-13/8	360	610	81	2.0	1270	15.9	20.5	0.346
15.2 ext.	20/8-03/9			12	0.3	1120	18.0	21.7	n.d.
Clay soil									
11.1	27/4-06/5	420	601	21	0.3	1454	12.5	17.4	0.272
11.1 ext.	19/5-26/5			1.0	0.1	1995	12.6	19.9	n.d.
Peat soil									
11.2	27/4-06/5	420	601	10	0.3	1454	13.4	19.1	0.477
11.2 ext.	19/5-26/5			2.5	0.5	1995	13.0	21.1	n.d.

Table 6. Experimental conditions and ammonia volatilization during the experiments with decaying grass and manure in 1987.

No. exp.	Period 1987	Fresh weight	Dry matter weight	N-applied Total N	N-applied NH_4^+-N	NH_3 volatilization In period	NH_3 volatilization In last 24 hours	Mean global daily radiation	Mean temperature (°C) of decaying grass or manure at 8.00 AM	Mean temperature (°C) of decaying grass or manure at 4.00 PM
		$kg\ m^{-2}$	$kg\ m^{-2}$	$kg\ ha^{-1}$	$kg\ ha^{-1}$	$kg\ N\ ha^{-1}$	$kg\ N\ ha^{-1}$	$J\ cm^{-2} day^{-1}$		
Decaying grass										
12.1	7/5-19/5	1.82	0.27	103	-	3.3	0.7	1419	11.5	16.1
12.2	7/5-19/5	1.82	0.27	103	-	2.3	0.3	1419	11.5	16.1
Manure										
13.1	1/7-13/7	31.8	4.4	1247	93	128	7.3	2224	18.7	33.8
13.1 ext.	24/7-30/7					3.6	0.4	1011	16.6	19.8
13.2	1/7-13/7	31.8	4.4	1247	93	117	3.9	2224	20.0	36.5
13.2 ext.	24/7-30/7					2.9	0.3	1011	17.2	20.6

Table 7. Ammonia-N volatilization, kg ha^{-1}, in consecutive day (D)- and night (N)-periods in the experiments on sandy soil in 1986 and 1987.

Sampling period	Number of the experiment																	
	1.1	2.1	1.2	2.2	3.1	3.2	4.1	4.2	5.1	5.2	6.1	6.2	7.1	7.2	14.1	14.2	15.1	15.2
1 D	11.5	6.1	23.7	21.2	10.4	24.8	19.9	15.8	24.3	26.4	21.5	19.7	8.4	17.0	7.0	11.4	10.4	12.8
1 N	3.9	1.3	7.7	5.6	1.6	6.7	8.2	4.3	5.3	13.1	7.1	11.2	12.8	10.2	2.4	4.2	12.1	14.1
2 D	5.4	1.8	22.9	5.9	3.2	6.6	10.8	8.4	5.6	10.7	14.7	14.8	7.4	14.5	2.0	3.1	12.0	13.9
2 N	0.9	1.6	2.7	2.6	0.5	1.8	1.7	2.4	1.6	3.4	2.6	3.6	1.7	6.6	1.1	1.6	5.0	5.9
3 D	2.7	0.9	11.7	1.7	1.2	2.6	3.2	2.3	6.0	6.9	5.7	5.1	7.1	9.9	1.8	2.0	5.8	6.8
3 N	0.5	0.2	1.3	0.6	0.2	0.7	1.0	0.9	0.6	1.3	1.0	1.7	4.0	1.8	0.7	0.9	2.2	2.7
4 D	1.3	0.5	6.1	0.8	1.2	1.6	4.1	2.1	3.8	4.3	3.0	3.0	4.0	5.6	0.7	0.9	3.9	4.6
4 N	0.3	0.1	1.3	0.3	0.2	0.4	0.8	0.6	0.4	0.6	0.5	0.9	0.6	1.9	0.4	0.5	1.7	2.2
5 D	1.3	0.5	5.0	0.8	1.2	1.3	2.6	1.5	3.0	3.4	2.5	2.5	2.3	2.2	0.7	0.9	3.1	3.8
5 N	0.2	0.2	0.8	0.2	0.2	0.3	0.4	0.2	0.2	0.4	0.2	0.5	0.2	1.4	0.1	0.1	1.2	1.7
6 D	0.7	0.9	3.2	0.7	1.4	1.3	2.2	1.0	2.6	2.9	1.7	2.0	3.8	4.5	0.4	0.5	1.4	1.7
6 N	0.2	0.1	0.8	0.0	0.1	0.1	0.3	0.1	0.1	0.2	0.1	0.3	0.6	0.5	0.1	0.0	0.8	1.0
7 D	0.5	0.5	2.8	0.3	0.7	0.4	1.9	0.8	1.9	1.9	1.5	1.4	2.2	4.1	0.3	0.2	1.1	1.4
7 N	0.1	0.0	0.6	0.0	0.1	0.1	0.3	0.0	0.1	0.1	0.1	0.2	0.3	0.4	0.1	0.0	0.7	0.9
8 D	0.5	0.6	2.3	0.2	0.6	0.5	1.7	0.6	1.6	1.4	1.0	0.9	1.6	2.5	0.3	0.3	2.1	2.4
8 N	0.1	0.1	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.1	0.2	0.7	0.2	0.1	0.1	0.3	0.4
9 D	1.1	0.8	1.9	0.3	0.7	0.4	1.6	0.7	1.8	1.4	1.5	1.3	4.0	3.5	0.4	0.4	1.8	2.3
9 N	0.2	0.0	0.4	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.1	0.3	1.3	0.1	0.1	0.4	0.6
10 D	1.3	0.4	2.4	0.1	-	-	0.3	0.0	3.8	2.7	1.7	1.4	2.3	4.8	0.3	0.3	0.9	1.4
10 N	0.2	0.0	0.4	0.0	-	-	0.0	0.0	0.1	0.1	0.2	0.3	1.1	0.3	0.1	0.1	0.2	0.6

Table 8. Ammonia-N volatilization, kg ha^{-1}, in consecutive day (D)- and night (N)-periods in the experiments on clay and peat soil in 1986 and 1987 and in the experiments with decaying grass and manure in 1987.

Sampling period	Number of the experiment									
	8.1	9.1	11.1	8.2	9.2	11.2	12.1	12.2	13.1	13.2
1 D	3.8	2.4	3.8	4.1	3.9	0.9	0.0	0.0	0.8	0.9
1 N	4.1	3.2	3.5	1.8	6.9	0.9	0.0	0.0	0.2	0.2
2 D	5.8	5.4	4.5	5.3	14.4	1.8	0.1	0.1	1.7	2.2
2 N	3.3	2.9	2.1	1.6	11.0	0.9	0.0	0.0	3.0	2.8
3 D	3.2	2.2	2.0	6.0	8.7	1.2	0.2	0.2	10.2	13.8
3 N	1.3	1.0	1.5	1.1	3.9	0.7	0.1	0.1	2.2	3.0
4 D	1.8	1.5	1.0	4.4	4.6	0.7	0.0	0.1	13.6	17.6
4 N	0.6	0.6	0.7	0.5	2.4	0.5	0.0	0.0	3.4	3.6
5 D	1.1	1.3	0.4	2.1	3.6	0.5	0.0	0.1	16.6	16.2
5 N	0.6	0.6	0.3	0.5	1.9	0.4	0.0	0.0	3.3	3.0
6 D	0.9	0.8	0.4	1.7	1.9	0.5	0.1	0.0	14.1	13.4
6 N	0.4	0.3	0.2	0.3	1.0	0.2	0.0	0.0	3.1	2.4
7 D	0.8	0.7	0.1	1.8	1.8	0.2	0.1	0.1	11.7	10.5
7 N	0.4	0.3	0.1	0.6	0.9	0.2	0.0	0.0	3.0	2.2
8 D	0.7	0.7	0.1	1.7	1.7	0.1	0.1	0.1	7.7	6.5
8 N	0.4	0.3	0.0	0.5	0.8	0.1	0.1	0.1	2.0	1.2
9 D	0.4	0.7	0.1	0.9	1.8	0.2	0.2	0.1	6.5	4.5
9 N	0.2	0.2	0.2	0.2	0.8	0.1	0.2	0.1	1.7	0.8
10 D	0.5	0.6	-	1.1	1.8	-	0.3	0.2	4.3	2.1
10 N	0.2	0.2	-	0.3	0.6	-	0.2	0.1	2.5	1.1
11 D							0.4	0.2	7.1	4.2
11 N							0.4	0.2	2.1	0.8
12 D							0.4	0.2	5.8	3.4
12 N							0.3	0.1	1.5	0.6

Table 9. Ammonia-N volatilization, kg ha^{-1}, in consecutive day (D) and night (N)-periods in the extended periods of the experiments in 1987.

Sampling period	No. experiment 11.1	11.2	Sampling period	No. experiment 13.1	13.2	Sampling period	No. experiment 14.1	14.2	Sampling period	No. experiment 15.1	15.2
23 D+N	0.4	0.5	24 D	0.2	0.3	31 D	0.2	0.2	18 D	0.4	0.8
			24 N	0.2	0.1	31 N	0.1	0.2	18 N	0.3	0.8
									19 D	1.1	2.2
24 D+N	0.1	0.3	25 D	0.8	0.7	32 D	0.2	0.2	19 N	0.2	0.6
			25 N	0.1	0.1	32 N	0.0	0.0	20 D	0.5	1.1
									20 N	0.1	0.4
25 D+N	0.1	0.2	26 D	0.7	0.6	33 D	0.1	0.1	21 D	0.4	0.9
			26 N	0.2	0.2	33 N	0.0	0.0	21 N	0.0	0.4
									22 D	0.3	0.8
26 D+N	0.0	0.2	27 D	0.4	0.3	34 D	0.1	0.1	22 N	0.1	0.3
			27 N	0.1	0.0	34 N	0.1	0.0	23 D	0.2	0.4
									23 N	0.1	0.1
27 D+N	0.1	0.4	28 D	0.4	0.3	35 D	0.0	0.1	24 D	0.2	0.3
			28 N	0.1	0.1	35 N	0.0	0.0	24 N	0.1	0.1
									25 D	0.1	0.1
28 D+N	0.1	0.4	29 D	0.3	0.2	36 D	0.0	0.0	25 N	0.0	0.1
			29 N	0.1	0.1	36 N	0.0	0.0	26 D	0.1	0.2
									26 N	0.0	0.2
29 D+N	0.1	0.5				37 D	0.1	0.0	27 D	0.1	0.2
						37 N	0.0	0.0	27 N	0.0	0.1
									28 D	0.1	0.4
									28 N	0.0	0.1
									29 D	0.1	0.3
									29 N	0.0	0.0
									30 D	0.0	0.3
									30 N	0.0	0.1
									31 D	0.1	0.2
									31 N	0.1	0.1

Table 10. Soil surface pH measured at 8 A.M.
0* = initial value, 0 = maximum value on the first day of the experiment.

Days after	No. experiment																					
urine appl.	1.1	2.1	1.2	2.2	3.1	3.2	4.1	4.2	5.1	5.2	6.1	6.2	7.1	7.2	14.1	14.2	15.1	15.2	8.1	9.1	11.1	8.2	9.2	11.2
0*	6.04	n.d	6.19	n.d	5.83	5.83	6.00	6.34	5.97	5.85	6.60	5.75	6.33	5.61	5.63	5.37	6.00	5.98	7.59	7.59	7.57	5.07	5.00	5.12
0	8.15	7.73	8.55	8.42	8.00	8.25	8.51	8.41	8.31	8.82	9.04	8.86	8.91	8.78	8.10	8.40	8.82	9.12	8.24	8.04	8.43	7.68	7.96	8.36
1	7.65	7.64	8.38	8.47	8.19	8.26	8.66	8.11	8.45	8.69	9.12	8.90	8.93	8.67	8.22	8.44	8.88	9.09	8.30	7.98	8.56	7.90	8.35	8.77
2	7.53	7.24	8.22	8.20	7.21	7.92	8.58	7.93	8.08	8.60	8.51	8.59	8.76	8.46	7.81	8.12	8.99	9.00	8.16	8.00	8.47	8.30	8.22	8.49
3	7.22	6.89	8.12	8.08	7.13	8.03	8.20	7.62	7.91	8.27	8.05	8.34	8.29	8.13	7.59	7.90	8.74	8.81	7.81	8.08	8.24	8.38	8.32	8.06
4	6.98	6.83	8.26	8.02	6.99	7.97	7.77	7.62	7.07	7.77	8.05	8.11	8.03	7.90	7.36	7.44	8.60	8.82	7.69	7.94	8.23	8.03	7.79	8.25
5	7.16	7.09	7.61	7.74	7.62	7.36	7.58	7.41	7.88	7.90	7.98	7.99	7.64	8.08	7.22	7.18	8.57	8.78	7.82	7.93	7.99	7.91	7.94	8.22
6	6.82	7.12	7.78	7.50	7.33	7.66	7.30	6.61	7.26	7.58	7.62	7.74	8.16	7.98	7.07	6.94	8.24	8.39	7.83	7.59	-	7.80	8.28	-
7	6.42	6.54	7.70	7.15	6.58	7.48	6.98	6.52	7.32	7.68	7.42	7.63	7.96	7.99	6.53	6.54	8.07	8.35	7.58	7.64	7.97	7.40	[illegible]	8.18
8	6.59	6.45	7.78	7.04	6.35	7.03	6.71	6.35	6.43	7.09	7.53	7.71	8.04	7.88	n.d.	n.d.	8.17	8.48	7.50	7.70	7.94	7.33	7.96	8.15
9	6.54	6.10	7.48	7.08	6.56	7.09	6.84	6.45	7.51	7.59	7.47	7.58	8.04	7.84	6.13	6.19	7.91	8.50	7.48	7.53	7.83	7.72	7.76	7.91
10	5.71	5.82	7.43	7.13	-	-	7.07	6.59	6.35	7.22	7.29	7.07	8.00	8.01	6.36	6.04	8.03	8.37	7.41	7.48	-	7.55	7.98	-
11															-	-	7.76	7.94			-			-
14															-	-	6.86	7.74			-			-
16															-	-	6.48	7.43			7.62			7.69
18															-	-	5.73	7.30			-			-
21															6.84	8.80	5.63	7.17			7.53			7.16
23															-	-	5.81	7.09			7.73			7.62
25															-	-	6.05	6.83			7.90			7.44
27															-	-	5.88	6.79			-			-
29															6.27	6.47	6.03	6.75			7.31			6.38
31															5.94	6.14	6.14	6.78						
33															6.33	6.44								
35															5.98	6.06								
37															5.75	6.04								

Table 11. N budget over 10.day periods for the experiments in 1986.

No. exp.	Period 1986	Urine-N applied	N in soil (0-40 cm) at end of period						N uptake by the grass		NH_3 volatilization	N, not accounted for
			control			urine			control	urine		
			NH_4^+-N	NO_3^--N	inorg.-N	NH_4^+-N	NO_3^--N	inorg.-N				
		+			+			-	+	-	-	=
Sandy soil												
1.1	21/04-01/05	284	14	22	36	87	109	196	9	52	32	49
2.1	12/05-22/05	285	10	22	32	65	156	221	37	65	17	51
1.2	21/04-01/05	565	14	22	36	249	64	313	9	35	98	164
2.2	12/05-22/05	566	10	22	32	135	164	299	37	48	41	247
3.1	26/05-04/06	607	17	11	28	189	161	350	9	39	23	232
3.2	26/05-04/06	607	17	11	28	231	148	379	9	37	49	179
4.1	09/06-19/06	604	11	28	39	142	205	347	51	52	62	233
4.2	09/06-19/06	604	11	28	39	153	315	468	51	73	42	111
5.1	23/06-03/07	609	11	7	18	251	134	385	14	7	63	186
5.2	23/06-03/07	609	11	7	18	348	78	426	14	37	81	97
6.1	07/07-17/07	610	8	4	12	165	130	295	16	41	67	235
6.2	07/07-17/07	610	49	72	121	271	172	443	40	46	72	210
7.1	04/08-14/08	607	21	28	49	443	113	556	27	22	65	40
7.2	04/08-14/08	607	21	28	49	510	60	570	27	31	93	-11
Clay soil												
8.1	22/09-02/10	598	-	-	12*	146	93	239	20*	25	30	336
9.1	06/10-16/10	607	-	-	12*	193	138	331	20*	18	27	263
Peat soil												
8.2	22/09-02/10	598	-	-	30*	375	32	407	20*	11	35	195
9.2	06/10-16/10	607	-	-	30*	216	8	224	20*	8	76	349

* estimated values

Table 12. Nitrogen budgets over monthly periods for the experiments in 1987 (kg ha^{-1}).

No. exp.	Period 1987	Urine-N applied	N in soil (0-40 cm) at end of period						N uptake by the grass		NH_3 volatilization	N, not accounted for
			control			urine			control	urine		
			NH_4^+-N	NO_3^--N	inorg.-N	NH_4^+-N	NO_3^--N	inorg.-N				
		+			+			-	+	-	-	=
Sandy soil												
14.1	14/7-20/8	303	9	15	24	7	239	246	132	160	27	26
14.2	14/7-20/8	918	9	15	24	80	530	610	132	164	34	266
15.1	3/8- 3/9	610	8	17	25	18	441	459	68	34	81	129
15.2	3/8- 3/9	610	14	15	29	399	156	555	65	70	112	-33
Clay soil												
11.1	27/4-26/5	601	-	-	13*	14	63	77	100*	154	25	458
Peat soil												
11.2	27/4-26/5	601	-	-	12*	33	51	84	100*	155	17	457

* estimated values

Table 13. Ammonia volatilization from untreated grass swards.

Experiment	Period 1987	(NH_3) in air before tunnel	after tunnel	increase	NH_3 emission
			$\mu g\ m^{-3}$		$kg\ ha^{-1} (24\ h)^{-1}$
Sandy soil					
Tunnel 1	25/6-26/6	1.4	1.0	-0.4	-0.10
Tunnel 1	26/6-27/6	1.3	0.8	-0.5	-0.12
Tunnel 1	27/6-28/6	0.4	0.6	0.2	0.05
Tunnel 1	28/6-29/6	1.2	1.0	-0.2	-0.05
Tunnel 1	29/6-30/6	1.3	0.9	-0.4	-0.10
Tunnel 1	30/6- 1/7	1.3	0.8	-0.5	-0.12
Tunnel 2	25/6-26/6	1.1	1.4	0.3	0.07
Tunnel 2	26/6-27/6	1.1	0.8	-0.3	-0.07
Tunnel 2	27/6-28/6	1.1	0.6	-0.5	-0.12
Tunnel 2	28/6-29/6	1.1	0.9	-0.2	-0.05
Tunnel 2	29/6-30/6	1.1	1.0	-0.1	-0.02
Tunnel 2	30/6- 1/7	1.2	0.8	-0.4	-0.10
Clay soil					
Tunnel 1	22/4-24/4	0.6	1.3	0.7	0.17
Tunnel 1	24/4-27/4	0.6	1.4	0.8	0.19
Tunnel 1	6/5- 6/5	0.6	0.7	0.1	0.02
Tunnel 1	6/5- 7/5	0.6	0.5	-0.1	-0.02
Peat soil					
Tunnel 2	22/4-24/4	0.7	2.2	1.5	0.36
Tunnel 2	24/4-27/4	0.7	1.6	0.9	0.22
Tunnel 2	6/5- 6/5	0.7	1.4	0.7	0.17
Tunnel 2	6/5- 7/5	0.7	0.9	0.2	0.05

Table 14. Conditions inside the tunnel (in) compared to those outside (out) during the experiments in 1986 and 1987.

No. exp.	Period	Rainfall in experimental period mm	Mean temperature (°C) of the soil layer 0-3 cm at 8.00 A.M. in	at 8.00 A.M. out	at 4.00 P.M. in	at 4.00 P.M. out	Soil surface pH at end of period in	out	Soil moisture content of the layer 0-10 cm at end of period (ml ml^{-1}) in	out
Sandy soil										
1.1	21/04-01/05'86	11.8	10.3	7.5	13.2	11.6	5.81	5.71	0.386	0.394
2.1	12/05-22/05'86	10.7	14.2	12.4	19.0	17.0	6.05	5.82	0.354	0.386
1.2	21/04-01/05'86	11.8	10.3	7.5	13.2	11.6	7.01	7.43	0.386	0.371
2.2	12/05-22/05'86	10.7	14.2	12.4	19.0	17.0	6.94	7.13	0.354	0.367
3.1	26/05-04/06'86	10.7	14.2	12.6	19.4	18.6	6.67	6.56	0.373	0.381
3.2	26/05-04/06'86	10.7	14.2	12.6	19.4	18.6	6.83	7.09	0.340	0.360
4.1	09/06-19/06'86	4.7	17.5	16.0	22.3	21.7	6.80	7.07	0.279	0.316
4.2	09/06-19/06'86	4.7	17.5	16.0	22.3	21.7	6.54	6.59	0.266	0.310
5.1	23/06-03/07'86	21.6	20.8	18.8	27.9	26.4	6.77	6.35	0.144	0.273
5.2	23/06-03/07'86	21.6	20.8	18.8	27.9	26.4	7.15	7.22	0.099	0.233
6.1	07/07-17/07'86	2.3	17.7	16.4	21.8	21.2	7.77	7.29	0.127	0.170
6.2	07/07-17/07'86	2.3	17.7	16.4	21.8	21.2	7.68	7.07	0.119	0.173
7.1	04/08-14/08'86	7.8	17.7	16.4	22.4	21.4	7.78	8.00	0.210	0.288
7.2	04/08-14/08'86	7.8	17.7	16.4	22.4	21.4	7.76	8.01	0.214	0.266
14.1	14/07-24/07(*20/8)'87	98.1(*117.6)	19.2	18.1	23.7	21.2	6.81	6.36	0.271*	0.329*
14.2	14/07-24/07(*20/8)'87	98.1(*117.6)	19.2	18.1	23.7	21.2	7.31	6.04	0.256*	0.342*
15.1	03/08-13/08(*3/9)'87	43.3(*70.5)	15.9	14.3	20.5	18.6	7.75	8.03	0.327*	0.358*
15.2	03/08-13/08(*3/9)'87	43.3(*70.5)	15.9	14.3	20.5	18.6	8.09	8.37	0.332*	0.332*
Clay soil										
8.1	22/09-02/10'86	0.4	12.9	11.5	18.0	15.9	7.45	7.41	0.243	0.319
9.1	06/10-16/10'86	2.5	14.5	13.0	17.6	16.1	7.66	7.48	0.292	0.330
11.1	27/04-06/05(*26/5)'87	5.2(*22.5)	12.5	11.3	17.4	17.6	7.99	7.83	±0.229*	0.294*
Peat soil										
8.2	22/09-02/10'86	0.4	13.4	11.5	19.3	17.0	6.90	7.55	0.427	0.504
9.2	06/10-16/10'86	2.5	15.4	13.2	18.6	16.7	7.77	7.98	0.207	0.461
11.2	27/04-06/05(*26/5)'87	5.2(*22.5)	13.4	11.1	19.1	16.5	7.34	7.91	0.361*	0.477*

* extended period

Table 15. NH_4^+-N, NO_3^--N and total inorganic-N contents of the soil at end of period inside the tunnel (in) and outside (out) during the experiments in 1986 and 1987.

No. exp.	Period	Rainfall in experimental period mm	Inorganic N in soil (0-40 cm) at the end of period (kg ha^{-1})					
			NH_4^+-N		NO_3^--N		inorganic N	
			in	out	in	out	in	out
Sandy soil								
1.1	21/04-01/05 1986	11.8	87	97	109	78	196	175
2.1	12/05-22/05 1986	10.7	65	74	156	182	221	256
1.2	21/04-01/05 1986	11.8	249	314	64	48	313	362
2.2	12/05-22/05 1986	10.7	135	131	164	114	299	245
3.1	26/05-04/06 1986	10.7	189	265	161	219	350	484
3.2	26/05-04/06 1986	10.7	231	334	148	160	379	494
4.1	09/06-19/06 1986	4.7	142	133	205	226	347	359
4.2	09/06-19/06 1986	4.7	153	125	315	343	468	468
5.1	23/06-03/07 1986	21.6	251	179	134	171	385	350
5.2	23/06-03/07 1986	21.6	348	321	78	172	426	493
6.1	07/07-17/07 1986	2.3	165	151	130	123	295	274
6.2	07/07-17/07 1986	2.3	271	280	172	224	443	504
7.1	04/08-14/08 1986	7.8	443	363	113	78	556	441
7.2	04/08-14/08 1986	7.8	510	399	60	45	570	444
14.1	14/07-20/08 1987	117.6	7	7	239	84	246	91
14.2	14/07-20/08 1987	117.6	80	20	530	313	610	333
15.1	03/08-03/09 1987	70.5	18	14	441	479	459	493
15.2	03/08-03/09 1987	70.5	399	347	156	162	555	509
Clay soil								
8.1	22/09-02/10 1986	0.4	146		93		239	
9.1	06/10-16/10 1986	2.5	193	158	138	107	331	265
11.1	27/04-26/05 1987	22.5	14	75	63	116	77	191
Peat soil								
8.2	22/09-02/10 1986	0.4	375		32		407	
9.2	06/10-16/10 1986	2.5	216	271	8	14	224	285
11.2	27/04-26/05 1987	22.5	33	110	51	84	84	194