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The effects of management on ammonia fluxes over a cut grassland as measured by use of dynamic chambers

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Abstract

Grassland management may lead to strong modification of the canopy structure and hence fluxes of carbon and nitrogen in the soil-plant-atmosphere system. Mowing or grazing removes green leaves, which are often a sink for ammonia. Consequently, the ratio between actively growing leaves and senescing/dead parts of the plants is strongly changed in favour of the latter, which may constitute a large source of ammonia. Moreover, fertilisers are a known source of ammonia through direct volatilisation.

The effects of grassland management, e.g. growing, cutting and fertilisation, on ammonia emission were investigated using a dynamic chamber. This technique made it possible to monitor ammonia emissions in the field at the plant level. With ammonia-free air at the inlet, the ammonia emissions from mature sward did not exceed 4 ng NH_3 m^{-2} s^{-1}. They were approximately 20 times larger above a sward regrowing after cutting and 200 times larger after fertilisation, where 0.5–1.0% of the applied inorganic nitrogen fertiliser was lost by volatilisation.

Cutting implied three main changes in ammonia sources and sinks within the canopy: (i) physiological changes with nitrogen remobilisation to the growing leaves and increase in senescence, (ii) changes in compartment proportions with only 5% of green leaves remaining after cutting as opposed to equal proportions of dead leaves as green leaves before cutting, (iii) microclimate changes within the canopy especially for litter with higher turbulence, temperature, and alternation of dry (day) and wet (night) conditions after cutting. These changes promoted ammonia volatilisation from the litter, which could account for the increased ammonia loss following cutting. Another potential source was the wounded surfaces of the stubble which may have emitted ammonia during bleeding and evaporation of sap containing significant levels of ammonium.

These results showed that the contribution of litter and drying cut sward on the ammonia balance of grassland is very significant, as well as their interaction with microclimatic conditions. This could apply to most natural and managed ecosystems and could be especially significant in the former. Consequently, further studies on ammo-

nia fluxes should have a focus on this part of the canopy.

1 Introduction

Even though the main sources of atmospheric ammonia are livestock and commercial fertilisers, emission from the vegetation can contribute with 10% to total ammonia emission in Western Europe (ECETOC, 1994; Hutchings et al., 2001; Hyde et al., 2003; Reidy et al., 2008). Crops from intensive agriculture are generally considered as a source of atmospheric ammonia (Schjoerring and Mattsson, 2001) while the semi-natural ecosystems act as ammonia sinks (Sutton et al., 1993; Fléchard and Fowler, 1998). As a consequence, the vegetation plays a significant role in regulating atmospheric ammonia.

Grasslands represent a large fraction of agricultural area, with a wide range of management options, including fertiliser application, cutting for hay or silage production and grazing. Differences in intensification, often linked with soil type and climate, lead to differences in grassland management, from extensive sward regarded as a semi-natural ecosystem to intensive sward where much nitrogen is applied. Then grasslands may be either a source or a sink for atmospheric ammonia (Sutton et al., 2001; Sutton et al., 2008; Wichink Kruitt et al., 2007; Denmead et al., 2007). Up to now, little is known about the effects of the grass crop itself and of grassland management on ammonia exchange (Dabney and Bouldin, 1985; Harper et al., 2000; Wichink Kruitt et al., 2007).

The purpose of the present work was to investigate ammonia cycling within an intensively managed grassland in order to identify the main sources of ammonia linked to grassland management. The measurements were made on a fertilised sward managed for silage production in Northern Germany. Dynamic chambers were used to assess the effects of grassland management on ammonia exchanges at the plant level. Growing, cutting and fertilising periods were studied. We first focus on canopy changes induced by cutting and their effects on ammonia sources and sinks. Then we draw up the ammonia exchange in relationship with silage management and fertilisation.

2 Materials and methods

2.1 Dynamic chamber and gas concentration monitoring

The dynamic chamber used for continuous monitoring of ammonia and water vapour fluxes in the field had a volume ranging from 20 to 65 l, fitted to plant height. The airflow entering the chamber at a rate of 30–40 l mn^{-1} was filtered for ammonia, cooled and dried. Under such conditions, only emissions could be measured in the dynamic chamber. The ammonia concentration at the outlet of the chamber was measured with two types of wet effluent denuder tubes using an acid absorption solution ($NaHSO_4 \cdot 2H_2O$, 0.5 g l^{-1}). The first one, the TULIPA sensor (Cellier et al., 2000), was a vertical denuder (50 cm long×0.4 cm internal diam.) with a measurement time step of 60 or 120 min. The stripping solution was first stored in an automatic-sampler unit in the field and its ammonium concentration was measured in the laboratory by conductometry with an AMANDA measurement cell. The second ammonia sensor was an AMANDA (Anasys B.V., Albergen, the Netherlands; Wyers et al., 1993) with on-line analysis (time step of 5 min). The water vapour pressure was measured at the inlet and at the outlet of the dynamic chamber using a capacitive hygrometer (Vaisala, Helsinki, Finland). Temperatures were monitored inside (air, surface and soil) and outside (air) the dynamic chamber with copper-constantan thermocouples (Thermoelectric, Limeil Brevannes, France). Further details of the chamber are given by David et al., 2009.

2.2 Field measurements

2.2.1 Description of the measurement site

The measurements were carried out in Braunschweig, (south-east of Lower Saxony, Germany), in May–June 2000 during a joint field experiment as a part of the GRAMINAE project (Sutton et al., 2008). The site was a 18 ha grassland on a sandy soil with *Lolium perenne* L. as the dominating species. Plots of 10×10 m were established in the northern edge of the field for the dynamic chamber measurements.

The solar radiation was measured at 2 m height above the soil surface with a CM6B pyranometer (Kipp and Zonen, Delft, The Netherlands). On the main field, the temperature profile was measured in and above the canopy (at 2, 10, 20, 40, 70, 100, 140 and 200 cm above the soil surface) with copper-constantan thermocouples (Thermo-electric, Limeil Brevannes, France).

2.2.2 Treatments – sampling of plant material

Three dynamic chambers were available simultaneously for treatment comparisons. Three measurement periods made it possible to cover the main stages of grassland management:

Growing: Ammonia fluxes were measured by use of an AMANDA analyser above a mature sward a few days before cutting (29 May 2000–1 June 2000).

Cutting: Measurements of ammonia fluxes were performed above cut sward on 2 June 2000 using an AMANDA analyser and between the 3 June 2000 and 7 June 2000 using a TULIPA sensor. The grass was cut at a height of 5 cm on 30 May and on 2 June 2000, respectively. The hay was removed after a short drying period, according to usual silage production.

Fertilisation: Ammonia fluxes were measured over cut grassland after fertilisation (7–10 June 2000). One plot was fertilised with 100 kg N ha^{-1}, corresponding to the N treatment in the main field (Sutton et al., 2008). Other plots were either unfertilised or applied 200 kg N ha^{-1}. The pellets, applied on 7 June 2000, i.e. 5 days after cutting, were made of 26% $CaCO_3$ and 74% NH_4NO_3. On 9 June 2000 at 4:10 p.m., 600 g of water, corresponding to 6.7 mm, was added in each chamber to assess the effect of pellets dissolution on ammonia emissions and to reproduce a rain which occurred on the main field.

At the end of each measurement period, all the vegetation above the soil surface inside the dynamic chamber was picked up, split into stems, green and senescent or dead leaves, and inflorescences if present. LAI was measured and dry matter weights recorded after drying for 48 h at 80°C.

2.3 Measurements under controlled conditions

Complementary measurements were performed under controlled conditions in a climatic growth chamber (24–26 September 2001) in Grignon (Ile de France, France). The ammonia emissions from cut grass were investigated. This latter was cut at 5 cm height in a sward plot (*Lolium perenne* L.) in Grignon. A sample of 31.8 g fresh weight (FW) of cut herbage was put in an unsealed stainless steel box (300×200×60 mm) used as a dynamic chamber. The nitrogen content of the green leaves was measured by the Dumas method using an elemental analyser (NA 1500, Fisons-Instrument, Thermo Finnigan, Les Ulis, France). The ammonia concentration in the outlet of the dynamic chamber was monitored with an AMANDA during 2 days without opening the chamber. The temperature was kept constant at 19.3±0.4°C. The relative humidity in the chamber was kept above 87% to avoid a too fast withering of the hay considering the high flow rate of the air entering the dynamic chamber (average 44 l mn^{-1}, i.e. renewal rate larger than 10 volumes per minute).

The bulk tissue ammonium concentration was measured before and after the experiment following extraction in deionized water as described by David et al., 2009.

3 Results

3.1 Dynamic chamber

Figure 1 shows the difference in microclimatic conditions between inside and outside the chamber for tall grass and cut grass. Despite the drying/cooling unit (David et al., 2009), differences in environmental parameters were observed. The differences were more or less important depending on the type of vegetation inside. Air temperature bias was low above tall plants (Fig. 1). In contrast, the temperature was greater by more than 5°C above cut plant in the dynamic chamber compared to outside (Fig. 1). Such a difference could double the compensation point for ammonia (Schjoerring et al., 2000).

Conversely, changes in relative humidity due to the chamber was much less above cut plants than above tall plants (Fig. 1). In the latter case, the drying up of the air entering the dynamic chamber could not balance plant evapotranspiration. Above cut grassland, the air in the dynamic chamber was generally dryer than outside at night time and for a large fraction of the day, due to the efficiency of the drying/cooling unit.

3.2 Biomass by compartments

Table 1 gives the details of the composition of the harvested part of the sward (herbage picked up for silage) and of the vegetation remaining on the field after cutting (referred to as stubble hereafter). Considering the canopy biomass above the soil surface before cutting (stubble plus exported cut grass), dead leaves and green leaves represented each approximately 20% of the total dry biomass, stems 50% and inflorescences 10%. Dead and green leaves represented 38% of the harvested herbage and the stubble was composed of 50% of dead leaves and only 5% of green leaves (Table 1).

3.3 Tall plants

The ammonia emission above tall plants of *Lolium perenne* L. in the dynamic chamber during the Braunschweig field experiment was weak. It did not exceed 4 ng m^{-2} s^{-1} (Fig. 1a) and described a diurnal cycle with no exchange during the night and very small release during the day. The ammonia emission increased with solar radiation. These fluxes above mature sward were close to the detection limit of the chamber system, even if ammonia concentration were measured with an AMANDA analyser. The nitrogen content of the green leaves, was low (1.82% on a dry matter basis) and their water content was 76%.

3.4 Cutting

The ammonia fluxes above the sward re-growing after cutting were generally in the range 50–75 ng NH_3 m^{-2} s^{-1} at midday with a large peak (200 ng NH_3 m^{-2} s^{-1}) on a very sunny day (Fig. 1b). This is more than tenfold those above tall plants. They showed a diurnal pattern with weak and relatively constant emissions (10–40 ng NH_3 m^{-2} s^{-1}) at night time. The ammonia emissions were lower in the dynamic chamber than those measured outside with micromet methods (Milford et al., 2008), where ammonia fluxes of 300 ng NH_3 m^{-2} s^{-1} above the main field were measured in the middle of the day.

The experiment carried out under controlled conditions added a piece of information on ammonia exchanges from cut herbage. The ammonia emissions by the harvested sward part increased steadily for more than 36 h and reached 18 ng NH_3 m^{-2} leaf area s^{-1} (Fig. 2) while the leaf total ammonium concentration decreased from 4.9±0.18 µmol g^{-1} FW to 0.07±0.05 µmol g^{-1} FW (from 6.4 mM to 1 mM with 1 mM=1 µmol g^{-1} dead leaf water). Moreover, equilibrium flux was not reached at the end of this experiment.

3.5 Fertilisation

Ammonia emissions were much larger after fertilisation, with fluxes tenfold larger than above cut plants. They reached 700 ng NH_3 m^{-2} s^{-1} above the plot applied 100 kg N ha^{-1} and 1400 ng NH_3 m^{-2} s^{-1} above the 200 N-fertilised plot two days after application (Fig. 3). The dynamics of the ammonia fluxes were similar to that occurring over the main field (Milford et al., 2008), but their magnitude was lower.

Adding water increased rapidly the ammonia emissions. Particularly, the ammonia releases were higher during the night following the watering than the night before. However, during the following daytime, the volatilisation was similar to that occurring during the daytime before water addition. So the water-adding effect was short-lived. Relative humidity in the dynamic chamber rapidly decreased to 32% on 12:00 10 June

2000 (24 h after watering). It was 40% on 12:00 9 June 2000 just before watering, showing that the effect of water addition was also short-lived.

4 Discussion

4.1 Ammonia sources and sinks before and after cutting

Grassland management implies a succession of canopy types varying from short canopy (0.05 m) just after cutting to tall canopy (>0.5 m) before cutting. Grassland was a weak ammonia source before cutting, when exposed to ammonia-free air in the chamber. Under field conditions, with an atmospheric ammonia concentration of $3\,\mu g\,NH_3\,m^{-3}$, and considering the observed ammonia compensation point (Mattsson et al., 2008), it would be a sink. This was observed from micromet measurement in the nearby field by Milford et al., 2008. These fluxes above mature sward were close to the detection limit of the chamber system. Indeed the measured ammonia concentrations ($<0.4\,\mu g\,NH_3\,m^{-3}$,) were just above the ammonia concentration of the air provided by the acid filter (0.2–$0.3\,\mu g\,NH_3\,m^{-3}$). The ammonia fluxes could have been underestimated due to condensation on the chamber walls, where ammonia might be trapped on water films (Wichink Kruit et al., 2007). Consequently, the periods where condensation was visually observed on the chamber walls were removed from analyses. This occurred mainly during sunny and warm days above mature sward due to large evaporation in these conditions.

Our results confirmed the increase in net ammonia emissions after cutting as reported by Dabney and Bouldin (1985) and Milford et al., 2008. This could be explained by different processes related either to plant physiology, changes in canopy composition and microclimate.

- Green leaves exchange gases mainly via stomata (Farquhar et al., 1980). During this experiment, measurement on the leaf apoplasm after extraction using the vacuum infiltration technique showed low bulk and apoplastic ammonium concentration (Herrmann et al., 2009; Mattsson et al., 2008). Calculated plant ammonia compensation point was less than 1 µg NH_3 m^{-3}, and hence green leaves were regarded as a sink according to the atmospheric ammonia concentration (Sutton et al., 2008). However, defoliation is known to induce major modifications in carbon and nitrogen metabolism of grass (Volenec et al., 1996). While mineral nitrogen uptake and assimilation decrease after defoliation, nitrogen is remobilised from proteins in stubble and roots to growing leaves (Ourry et al., 1990; Massad et al., 2008). During senescence-induced nitrogen remobilisation, proteins are hydrolyzed into amino acids, which are de-aminated and the liberated ammonium at least partly incorporated into the transport amides glutamine and asparagine. This remobilisation speeds up leaf sheath senescence (Ourry et al., 1989) and increases ammonia emission rates (Schjoerring et al., 2000; Massad et al., 2008).

- After cutting, the relative proportions of different plant compartment also change. The dead leaves, which could be quickly mineralised and produce ammonium, represented approximately half the stubble (% DW) but only 20% of a mature sward (Table 1). The ammonium concentration of the litter (senescing, dead and decomposing leaves) was high (Mattsson et Schjoerring, 2003) and this compartment was considered as a significant ammonia source (David et al., 2009). Ammonia emissions from litter may occur under either a tall or a short canopy, but their magnitude and their effect on the net exchanges will differ between cut and tall grass. Indeed, the green leaves which are fully functional and mainly located above the dead leaves before the cut may therefore recapture a significant fraction of ammonia emitted by the litter in a mature sward as suggested for an oilseed rape canopy by Nemitz et al. (2000a) or for a grassland by Loubet et al. (2002) and Nemitz et al., 2009. Moreover, green leaves were not only less abundant after the cut, but their compensation point was also higher (Mattsson et al., 2008), which decreased their potential foliar uptake of ammonia.

- The third difference between a mature sward and a sward after defoliation is related to microclimate. Temperature and relative humidity are especially important in determining ammonia fluxes. Changes in microclimatic conditions are particularly pronounced for litter before and after the cut. Before cutting, the litter is protected from solar radiation and wind by the overlying green leaves and stems, while after cutting it is directly exposed to solar radiation and to turbulence. Microclimatic measurements inside the dynamic chamber showed a strong increase in leaf and surface temperatures. This was also observed in the field by monitoring the temperature of different types of leaves during the whole experiment (Nemitz et al., 2009). Figure 4 makes a synthesis of these measurements and shows that, during daytime, the relation between solar radiation and temperature differences was not the same before and after the cut. Increase in vegetation temperature results from both larger exposure to solar radiation and changes in micrometeorological conditions at field scale. As a matter of fact, the energy balance of the surface is very different before and after cutting, with grass evaporating efficiently a large fraction of the net radiation before the cut, which limits temperature increase. After the cut, the surface is mostly composed of bare soil and dry leaves or stems which convert a large fraction of radiation to sensible heat (Cellier et al., 1996), thus resulting in an increase in surface temperature. The difference between vegetation temperature and air temperature (2 m) was always less than 5°C before cutting for both dead and green leaves (generally less than 2–3 °C for green leaves). After cutting, it often reached 5°C for green leaves and 10–15 °C for dead leaves (hourly values). Such differences will increase the ammonia compensation point by a factor of 2 to 5. Cutting the grass also decreased relative humidity due to lower evapotranspiration (LAI was 3.1 before cutting and 0.3 just after cutting) and higher temperature. However, during the night the material lying on the ground is more exposed to dew deposition than in tall grass. This promotes water absorption by the dead organic matter and production of ammonium by mineralization. These marked alternations of wet and dry periods could increase ammonia emissions from the litter (David, 2002) in cut grassland. The changes in microclimatic conditions were less pronounced in the chamber because the cooling-drying unit diminished the occurrence of dew.

Besides the litter, another potential ammonia source should be pointed out. After clipping, xylem was bleeding due to the root pressure. Sap ammonium concentration can be as high as several mM (von Wiren et al., 2001; Mattsson and Schjoerring, 2002) in Graminaceae. Then the stubble could emit ammonia by evaporating sap from surface wounded by cutting. To verify this hypothesis, also proposed by Herrmann et al., 2008 for such case and by David et al., 2009 for remaining stumps in bare soil, a simplified calculation can be made. Assuming that only 1% of measured evapotranspiration in the chamber was coming from the cut surface of the blades of grass, with an ammonium concentration in the sap of 3 mM, it would produce an emission of 25 ng NH_3 m^{-2} s^{-1}. Therefore, this could contribute to ammonia flux during the first hours after cut. However, this phenomenon should be short-lived because the root uptake is quickly suppressed after cutting (Ourry et al., 1990) and the stubble and leaves should also quickly heal.

Ammonia emissions from the soil itself were expected to be low (Schjoerring et al., 1993; Neftel et al., 1998; Nemitz et al., 2000a). However, cutting made the soil more exposed to atmospheric turbulence and solar radiation. This could have promoted emissions as discussed by David et al., 2009.

4.2 Silage or hay management

Following defoliation, cut grass could also contribute to ammonia exchange (Whitehead et al., 1988). In the case of silage production, cut grass can be lifted after only one or two days, but for hay production, it can be left in the field for a longer time, with a rapid drying ensuring a better forage quality. The presence of cut grass lying on the regrowth can have two effects on ammonia exchanges after the cut. Firstly, it could be a source of ammonia. Secondly, it could intercept ammonia emission from underlying sources, the litter and the wounded stubble surfaces, and could increase resistance to diffusion of ammonia from the soil/stubble surface to the atmosphere (Tuzet et al., 1993).

Similar to ammonia emission from litter (Nemitz et al., 2000b; David et al., 2009), ammonia emission from cut herbage may depend on pH, ammonium concentration and temperature. Approximately 40% of the cut sward consisted of dead and green leaves (Table 1). This type of biological material can be quickly mineralised due to leaves composition, with high content of soluble organic matter and low content of lignin (Quemada and Cabrera, 1995). However, mineralization can only happen if water is present (Stott et al., 1986; Quemada and Cabrera, 1997). The results of the experiment carried out under controlled conditions (Fig. 2) showed that cut herbage was an ammonia source. However the experiment was made under high relative humidity conditions (90%), and so the drying was certainly slower than under natural conditions, which might lengthen the ammonia emission period: the water content of the cut herbage was 76% just after cutting at the beginning of the experiment and it was 70% at the end. This can happen during cloudy weather or after a rain as suggested by Whitehead et al. (1988) from hay remaining in the field for long time. These authors also measured ammonia volatilisation under classical drying conditions, but the fluxes were low.

Cut herbage, lying on the regrowing sward, represents a physical barrier, which may strongly increase the resistance to ammonia transfer from the cut sward to the atmosphere. Grassland on the main field in Braunschweig was managed as silage. The ammonia flux reached only 150 ng NH_3 m^{-2} s^{-1} during the two first days following cutting when hay was present. It increased to approximately 300 ng NH_3 m^{-2} s^{-1} after lifting of cut grass (Milford et al., 2008). This difference in the ammonia fluxes may be explained first by the weather. Indeed, it was raining just after the cut. But another reason could be the fact that drying hay could have obstructed ammonia emissions from litter and stubble. Using a resistance law of diffusion through a layer of hay (Tuzet et al., 1993), the calculated resistance from the top of the cut grass layer to the soil surface was multiplied by 2.5–3 compared to the same surface without a hay layer, hence decreasing the ammonia volatilisation.

4.3 Fertilisation

The studied sward was managed with a fertilisation of approximately 300 kg ha^{-1} y^{-1} in three applications. In the dynamic chamber, 0.25% of the applied N (200 kg N ha^{-1}) was lost during the second day following application. Assuming larger emissions during the day of application and the next one, the total losses should lie between 0.5 and 1% of applied fertilizer. As the ammonia emissions were divided by two for the chamber with 100 kg N ha^{-1}, the ratio should be the same for both treatments. These values are consistent with most published values of emission factors for ammonium nitrate (Asman and van Jaarsveld, 1992; ECETOC, 1994; Sutton et al., 1995) but in the low range. This could be explained by both the duration of the chamber experiment and the effect of the chamber. As a matter of fact, micrometeorological measurements in the field evidenced that volatilisation of the fertiliser lasted for more than 3 days (Milford et al., 2008) and flux measured in the dynamic chamber were generally lower than those measured in the field, certainly due mainly to limitation of turbulent transfer by the chamber but also by lower relative humidity which might slow granule decomposition.

The response of ammonia volatilisation from fertilizer granule to rainfall was consistent with earlier observations by Le Cadre et al. (2004). The low rainfall certainly speeded up the granule decomposition, hence promoting ammonium release from the fertiliser towards the soil surface. However, it must be recalled that a further rainfall could produce the reverse effect by decreasing the soil surface concentration in ammonium and, under extreme conditions, by leaching the ammonium (Génermont and Cellier, 1997).

5 Conclusions

Using dynamic chambers made it possible under field conditions to continuously measure ammonia emission at the plant level for different management events. Even though it modified the microclimatic conditions, especially wind speed, temperature and relative humidity, this type of method proved to be well adapted for comparing different treatments and distinguish between the different possible effects of grassland management. It allowed to monitor ammonia emission continuously in fair microclimatic conditions for several days and had a satisfactory sensitivity level. Similar comparisons would not have been possible with micromet methods because it requires large uniform fields where control is less easy.

The ammonia emissions were low (several ng m^{-2} s^{-1}) above mature sward. They were more than tenfold higher after cutting. The increase in ammonia emissions observed after cutting should be mainly explained by ammonia volatilisation from the senescing leaves and from the dead leaves. It was explained by the composition of the stubble, with a large proportion of dead and senescing leaves and no green leaves to recapture ammonia, by physiological processes linked to nitrogen remobilization after the cut, and by the change in surface conditions after the cut, which promoted larger temperature and wetting/drying cycles of the dead leaves. The cut sward itself was not shown to be a significant source of ammonia. The fertilisation was the main period contributing to total ammonia losses with emissions as large as several hundreds ng m^{-2} s^{-1}. Nitrogen losses were approximately 0.5–1% of the applied fertiliser. It was evidenced that emissions from the fertiliser were promoted by wet conditions but over a short period only. This study highlighted the importance of management options and the need to study the drying and decomposition of litter and cut grass as a source of ammonia. This might apply to analyse the sources of ammonia in other natural or managed ecosystems.

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References

Asman, W. A. H. and Jaarsveld, J. A. V.: A variable-resolution transport model applied for NH_x for Europe, Atmos. Environ., 26A, 445–464, 1992.

Cellier, P., David, M., and Loubet, B.: Mise au point d'une méthode de mesure de la teneur en ammoniac dans l'atmosphère. Programme Primequal – Predit. Convention ADEME – INRA No 98 93 027, Institut National de la Recherche Agronomique, Environnement et Grande Culture, Thiverval Grignon, 2000.

Cellier, P., Richard, G., and Robin, P.: Partition of sensible heat fluxes into bare soil and the atmosphere, Agr. Forest Meteorol., 82, 245–265, 1996.

Dabney, S. M. and Bouldin, D. R.: Fluxes of ammonia over an alfalfa field, Agron. J., 77, 572–578, 1985.

David, M.: Echanges d'ammoniac entre une prairie et l'atmosphère: sources et puits à l'échelle du couvert prairial et influence des pratiques agronomiques. PhD Thesis, Université Paris 11, INRA, p. 161, 2002.

David, M., Loubet, B., Cellier, P., Mattsson, M., Schjoerring, J. K., Nemitz, E., Roche, R., Riedo, M., and Sutton, M. A.: Ammonia sources and sinks in an intensively managed grassland using dynamic chambers, Biogeosciences Discuss, in press, 2009.

Denmead, O. T., Freney, J. R., and Dunin, F. X.: Gas exchange between plant canopies and the atmosphere: Case-studies for ammonia, Atmos. Environ., 42, 3394–3406, 2007

ECETOC: Ammonia emissions to air in western Europe, European Centre for Ecotoxicology and Toxicology of chemicals, Avenue E. Van Nieuwenhuyse 4, Brussels, 1994.

Farquhar, G. D., Firth, P. M., Wetselaar, R., and Weir, B.: On the gaseous exchange of ammonia between leaves and the environment: determination of the ammonia compensation point, Plant Physiol., 66, 710–714, 1980.

Flechard, C. R. and Fowler, D.: Atmospheric ammonia at a moorland site.II: Long term surface/atmosphere micrometeorological flux measurements, Q. J. R. Meteorol. Soc., 124, 759–791, 1998.

Génermont, S. and Cellier, P.: A mechanistic model for estimating ammonia volatilization from slurry applied to bare soil, Agric. Forest Meteorol., 88, 145–167, 1997.

Harper, L. A., Denmead, O. T., and Sharpe, R. R.: Identifying sources and sinks of scalars in a corn canopy with inverse Lagrangian dispersion analysis II. Ammonia, Agr. Forest Meteorol., 104, 75–83, 2000.

Herrmann, B., Mattsson, M., Jones, S. K., Cellier, P., Milford, C., Sutton, M. A., Schjoerring, J. K., and Neftel, A.: Vertical structure and diurnal variability of ammonia exchange potential within an intensively managed grass canopy, Biogeosciences, 6, 15–23, 2009, http://www.biogeosciences.net/6/15/2009/.

Hutchings, N. J., Sommer, S. G., Andersen, J. M., and Asman, W. A. H.: A detailed ammonia emission inventory for Denmark, Atmos. Environ., 35, 1959–1968, 2001.

Hyde, B. P., Carton, O. T., O'Toole, P., and Misselbrook, T. H.: A new inventory of ammonia emissions from Irish agriculture, Atmos. Environ., 37, 55–62, 2003.

Le Cadre, E., Génermont, S., Azam, F., and Recous, S.: The SAHGA model to calculate the Spatial Ammoniacal Heterogeneity at the soil surface after fertiliser Granule Application, Biol. Fertil. Soils, 40, 178–180, 2004.

Loubet, B., Milford, C., Hill, P. W., Tang, Y. S. T., Cellier, P., and Sutton, M. A.: Seasonal variability of apoplastic NH^{4+} and pH in an intensively managed grassland, Plant. Soil, 238, 97–110, 2002.

Massad, R. S., Loubet, B., Tuzet, A., and Cellier, P.: Relationship between ammonia stomatal compensation point and nitrogen metabolism in arable crops: Current status of knowledge and potential modelling approaches, Environ. Poll., 154, 390–403, 2008.

Mattsson, M., Herrmann, B., David, M., Loubet, B., Riedo, M., Theobald, M. R., Sutton, M. A., Bruhn, D., Neftel, A., and Schjoerring, J. K.: Temporal variability in bioassays of ammonia exchange potential in relation to plant and soil nitrogen parameters in intensively managed grassland, Biogeosciences Discuss., 5, 2749–2772, 2008, http://www.biogeosciences-discuss.net/5/2749/2008/.

Mattsson, M. and Schjoerring, J. K.: Dynamic and steady-state responses of inorganic nitrogen pools and NH_3 exchange in leaves of Lolium perenne and Bromus erectus to changes in root nitrogen supply, Plant Physiol., 128, 742–750, 2002.

Mattsson, M. and Schjoerring, J. K.: Senescence-induced changes in apoplastic and bulk tissue ammonia concentrations of ryegrass leaves, New Phytol., 160, 489–499, 2003

Milford, C., Theobald, M. R., Nemitz, E., Hargreaves, K. J., Horvath, L., Raso, J., Dmmgen, U., Neftel, A., Jones, S. K., Hensen, A., Loubet, B., Cellier, P., and Sutton, M. A.: Ammonia fluxes in relation to cutting and fertilization of an intensively managed grassland derived from an inter-comparison of gradient measurements, Biogeosciences Discuss., 5, 4699–4744, 2008, http://www.biogeosciences-discuss.net/5/4699/2008/.

Neftel, A., Blatter, A., Gut, A., Hoegger, D., Meixner, F. X., Ammann, C., and Nathaus, F. J.: NH_3 soil and soil surface gas measurements in a tritical wheat field, Atmos. Environ., 32, 499–505, 1998.

Nemitz, E., Sutton, M. A., Gut, A., San José R., Husted, S., and Schjoerring J. K.: Sources and sinks of ammonia within an oilseed rape canopy, Agr. Forest Meteorol., 105, 385–404, 2000a.

Nemitz, E., Sutton, M. A., Schjoerring, J. K., Husted, S., and Wyers, G. P.: Resistance modelling of ammonia exchange over oilseed rape, Agr. Forest Meteorol., 105, 405–425, 2000b.

Nemitz, E., Loubet, B., Lehmann, B. E., Cellier, P., Neftel, A., Jones, S. K., Hensen, A., Ihly, B., Tarakanov, S. V., and Sutton, M. A.: Turbulence characteristics in grassland canopies and implications for tracer transport, Biogeosciences Discuss., 6, 437–489, 2009, http://www.biogeosciences-discuss.net/6/437/2009/.

Ourry, A., Bigot, J., and Boucaud, J.: Protein mobilization from stubble and roots and proteoytic activities during post-clipping re-growth of perennial ryegrass, J. Plant Physiol., 134, 298–303, 1989.

Ourry, A., Boucaud, J., and Duyme, M.: Sink control of nitrogen assimilation during re-growth of ryegrass, Plant Cell Environ., 13, 185–189, 1990.

Quemada, M. and Cabrera, M. L.: Carbon and nitrogen mineralized from leaves and stems of four cover crops, Soil Sci. Soc. Am. J., 59, 471–477, 1995.

Quemada, M. and Cabrera, M. L.: Temperature and moisture effects on C and N mineralization from surface applied clover residue, Plant Soil, 189, 127–137, 1997.

Reidy, B., Rhim, B., and Menzi, H.: A new Swiss inventory of ammonia emissions from agriculture based on a survey on farm and manure management and farm-specific model calculations, Atmos. Environ., 42, 3266–3276, 2008.

Schjoerring, J. K., Husted, S., Mack, G., Nielsen, K. H., Finnemann, J., and Mattsson, M.: Physiological regulation of plant-atmosphere ammonia exchange, Plant Soil, 221, 95–102, 2000

Schjoerring, J. K., Kyllingsbaek, A., Mortensen, J. V., and Byskov-Nielsen, S.: Field investigations of ammonia exchange between barley plants and the atmosphere. I. Concentration profiles and flux densities of ammonia, Plant Cell Environ., 16, 161–167, 1993.

Schjoerring, J. K. and Mattsson, M.: Quantification of ammonia exchange between agricultural cropland and the atmosphere: Measurements over two complete growth cycles of oilseed rape, wheat, barley and pea, Plant Soil, 228, 105–115, 2001.

Stott, D. E., Elliott, L. F., Papendick, R. I., and Campbell, C. S.: Low temperature or low water potential effects on the microbial decomposition of wheat residue, Soil Biol. Biochem., 18, 577–582, 1986.

Sutton, M. A., Milford, C., Nemitz, E., Theobald, M. R., Hill, P. W., Fowler, D., Schjoerring, J. K., Mattsson, M., Nielsen, K. H., Husted, S., Erisman, J. W., Otjes R., Hensen, A., Mosquera, J., Cellier, P., Loubet, B., David, M., Génermont S., Neftel, A., Blatter, A., Herrmann, B., Jones, S. K., Horvath, L., Fuhrer E. C., Mantzanas, K., Koukoura, Z., Gallagher, M., Williams, P., Flynn, M., and Riedo, M.: Biosphere-atmosphere interactions of ammonia with grasslands: Experimental strategy and results from a new European initiative, Plant Soil, 228, 131–145, 2001.

Sutton, M. A., Nemitz, E., Theobald, M. R., Milford, C., Dorsey, J. R., Gallagher, M. W., Hensen, A., Jongejan, P. A. C., Erisman, J. W., Mattsson, M. E., Schjoerring, J. K., Cellier, P., Loubet, B., Roche, R., Neftel, A., Hermann, B., Jones, S., Lehman, B. E., Horvath, L., Weidinger, T., Rajkai, K., Burkhardt, J., Löpmeier, F. J., and Daemmgen, U.: Dynamics of ammonia exchange with cut grassland: strategy and implementation of the GRAMINAE Integrated Experiment, Biogeosciences Discuss., 5, 3347–3407, 2008, http://www.biogeosciences-discuss.net/5/3347/2008/.

Sutton, M. A., Pitcairn, C. E. R., and Fowler, D.: The exchange of ammonia between the atmosphere and plant communities, Adv. Ecol. Res., 24, 301–393, 1993.

Sutton, M. A., Schjoerring, J. K., and Wyers, G. P.: Plant-atmosphere exchange of ammonia, Phil. Trans. R. Soc. Lond., 351, 261–278, 1995.

Tuzet, A., Perrier, A., and Oulid-Aissa, A. K.: A prediction model for field drying of hay using a heat balance method, Agr. Forest Meteorol., 65, 63–89, 1993.

Volenec, J. J., Ourry, A., and Joern, B. C.: A role for nitrogen reserves in forage regrowth and stress tolerance, Physiologia Plantarum, 97, 185–193, 1996.

Whitehead, D. C., Lockyer, D. R., and Raistrick, N.: The volatilization of ammonia from perennial ryegrass during decomposition, drying and induced senescence, Atmos. Environ., 61, 567–571, 1988.

Wichink Kruit, R. J., Jacobs, A. F. G., Holtslag, A. A. M.: Measurements and estimates of leaf wetness over agricultural grassland for dry deposition modeling of trace gases, Atmos. Environ., 42, 5304–5316, 2007.

von Wirén, N., Gojon, A., Chaillou, S., and Raper, D.: Mechanisms and regulation of ammonium uptake in higher plants, In: Plant nitrogen, edited by: Lea, P. J. and Morot-Gaudry, J.-F., Springer-Verlag, Berlin – INRA éditions, Paris, pp. 61–77, 2001.

Wyers, G. P., Otjes, R. P., and Slanina, J.: A continuous-flow denuder for the measurement of ambient concentrations and surface-exchange fluxes of ammonia, Atmos. Environ., 27A, 2085–2090, 1993.

Table 1. Partition of the dry weight of different compartment – dead leaves, green leaves, stems and inflorescences – of the cut sward part and of the part remaining in the field after cutting (stubble; columns on the right). The samples were taken in the dynamic chamber, 27 May 2000, Braunschweig, Germany.

Plant compartment	% dry matter		
Stems	35		
Spikes	11		
Green leaves	20		
Dead material	7		
Stubble	27	**Stubble compartment**	**% dry matter**
		Stems	45
		Green leaves	5
		Dead material	50

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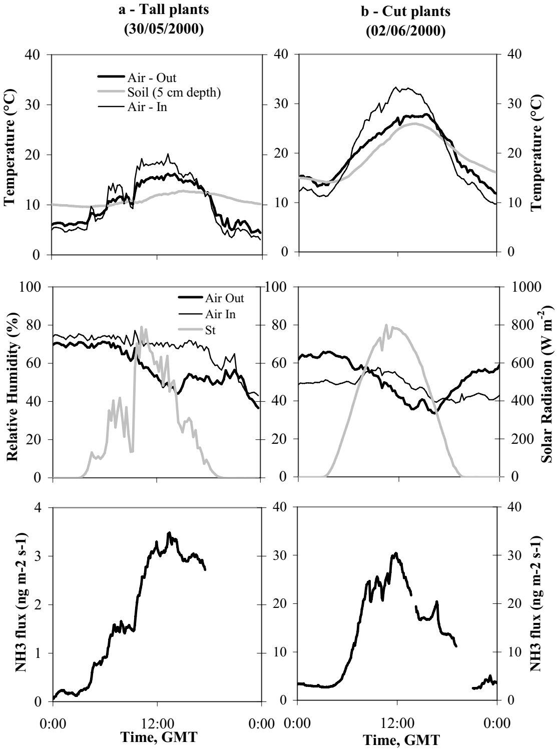

Fig. 1. Ammonia fluxes measured with the dynamic chamber and microclimatic conditions inside and outside the dynamic chamber over tall and cut sward.

- top graphs: air and soil temperatures
- middle graphs: relative humidity and solar radiation (St)
- bottom graphs: ammonia fluxes monitored with an AMANDA.

Field measurements on 30 May 2000 and 2 June 2000, Braunschweig, Germany.

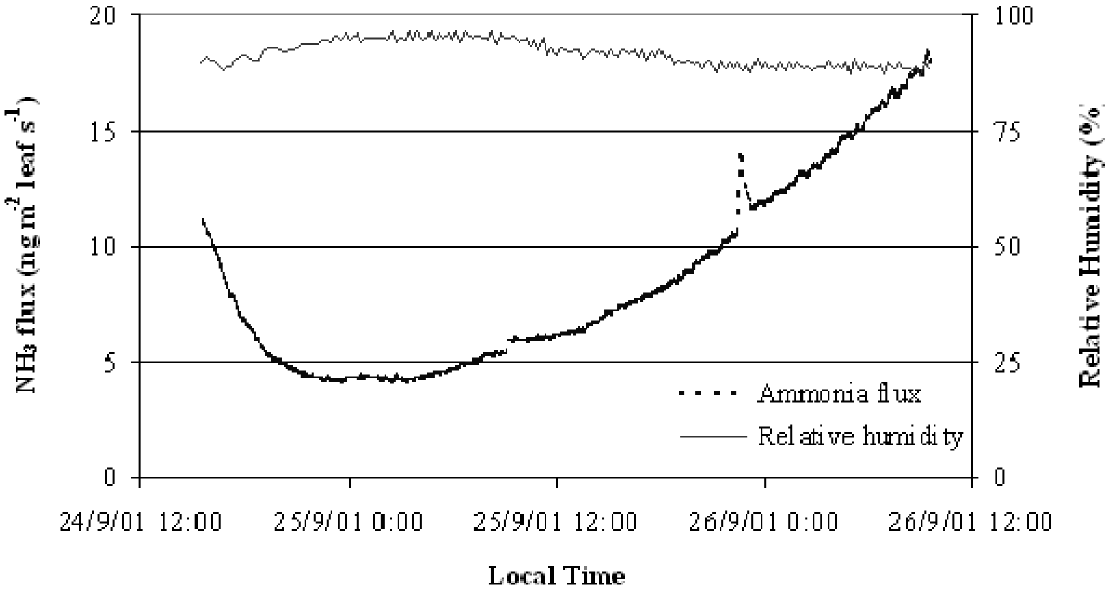

Fig. 2. Relative humidity and ammonia emission from grass just after cutting as measured under controlled conditions (19.3°C) in Grignon (France) 24–26 September 2001. Ammonia concentration was monitored using an AMANDA.

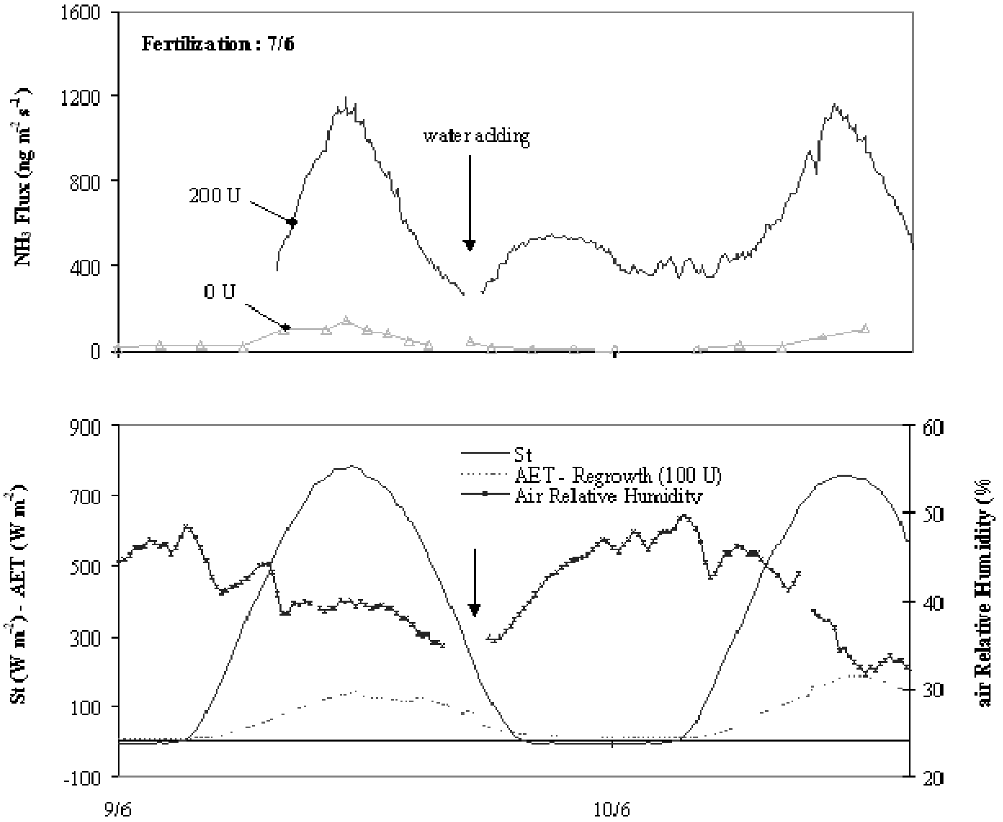

Fig. 3. Ammonia fluxes from cut grassland after nitrate-ammonium application (0 or 200 kg N ha^{-1}) monitored in dynamic chambers with an AMANDA for the fertilised plot and a TULIPA sensor for the control. The bottom graphs give the microclimatic conditions, with solar radiation, relative humidity and evapotranspiration.
Field measurements, 7–10 June 2000, Braunschweig, Germany.

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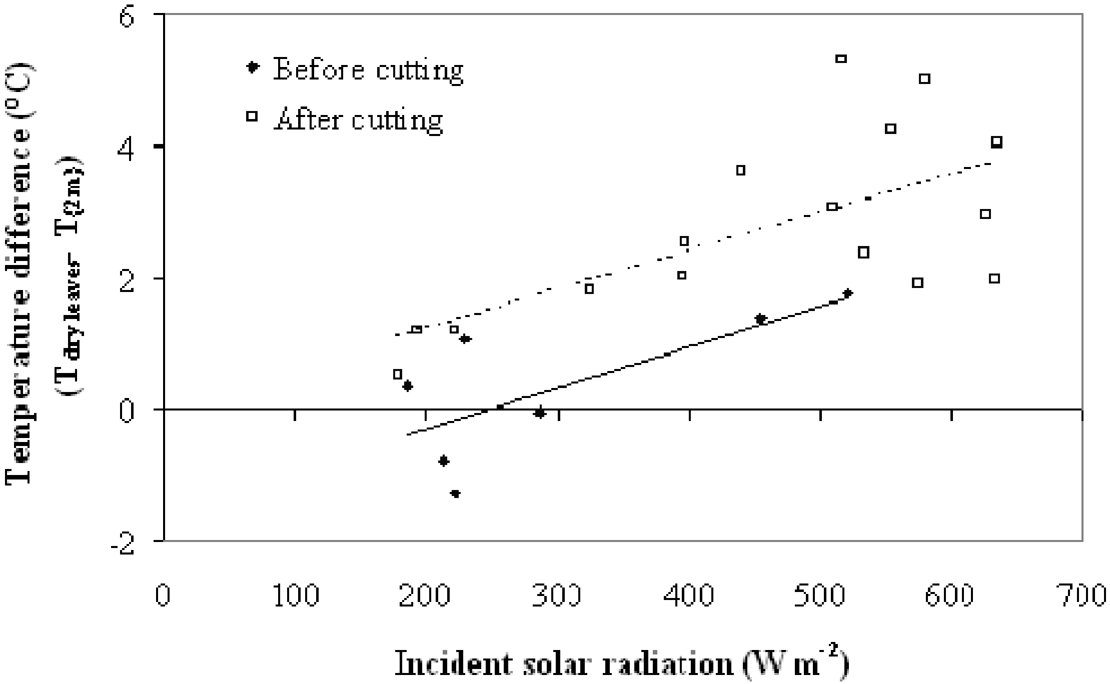

Fig. 4. Temperature difference between air at 2 m and dry leaves on the soil surface as a function of the incident solar radiation before and after the cutting. Each point was a daily mean (5:15–17:15) during the period 22 May–15 June 2000, Braunschweig, Germany.