Ammonia emission from crop residues

Quantification of ammonia volatilization based on crop residue properties

F.J. de Ruijter & J.F.M. Huijsmans

Ammonia emission from crop residues

Quantification of ammonia volatilization based on crop residue properties

F.J. de Ruijter & J.F.M. Huijsmans

Ministry of Infrastructure and the Environment

Plant Research International, part of Wageningen UR
Business Unit Agrosystems Research

Table of contents

1.   Introduction

To protect the environment, the European Union (EU) has adopted the National Emission Ceilings (NEC) directive (EC, 2001). This directive sets national goals for nitrogen oxides and ammonia emissions. Velthof *et al.* (2011) developed a new NH_3 inventory model for national emission registration in the Netherlands called NEMA (National Emission Model for Ammonia). This model adds up the emission from the various sources. Major sources for emission of ammonia (NH_3) and other gases are animal housing, manure storage and use of livestock manure and fertilizers on agricultural fields. Crops and crop residues may also contribute to ammonia volatilization, but sufficient information on their contribution to the national ammonia volatilization is lacking (Van Pul *et al.*, 2008; Velthof *et al.*, 2009).

Laboratory work has demonstrated that living plants can absorb NH_3 from the air (Farquhar *et al.*, 1980; Hutchinson *et al.*, 1972) and that losses of NH_3 from plant tissue occur (Farquhar *et al.*, 1980; Hooker *et al.*, 1980; Odeen and Porter, 1986; Schjoerring and Mattsson, 2001). Field studies have also shown losses and gains of NH_3 from crops (Denmead *et al.*, 1978; Harper *et al.*, 1987). The direction of exchange of NH_3 between plant and atmosphere depends on the difference between ammonia concentration in atmosphere and within the leaves. While at relatively high ambient concentrations NH_3 is absorbed, at concentrations below the so-called 'NH_3 compensation point' (Farquhar *et al.*, 1980), a net NH_3 release will occur. In an intensively managed grassland, (Harper *et al.*, 1996) measured within a period of 40 days a net NH_3 absorption of 2.3 kg N ha^{-1} in spring and 3.9 kg N ha^{-1} in summer. From a large field experiment on ammonia exchange processes in grassland, it was concluded that grassland management had a large effect on fluxes: emissions increased after grass cutting (-50 to 700 ngm^{-2} s^{-1} NH_3) and after N-fertilization (0 to 3800 ngm^{-2} s^{-1}) compared with before the cut (-60 to 40 ngm^{-2} s^{-1}) (Milford *et al.*, 2009; Sutton *et al.*, 2009).

Plant senescence generally leads to NH_3 emission. Under simulated environmental conditions with a wind tunnel method, (Mannheim *et al.*, 1997) measured NH_3 emission from maturing plant stands during four weeks. Emission ranged between 0.8 and 1.4% of the N content of the shoot, equivalent to 1.1 to 2.9 kg NH_3-N ha^{-1}.
In a standing crop, senescing leaves and leaf litter is a major source of NH_3. However, a significant part of the NH_3 emitted by leaf litter can be absorbed again by the foliage, thus reducing the net emission (Nemitz *et al.*, 2000; Sutton *et al.*, 2009).

N may also be lost as ammonia when crop residues are left on the soil surface. When residues are incorporated into the soil, ammonia volatilization is eliminated (De Ruijter *et al.*, 2010; Janzen and McGinn, 1991; Mohr *et al.*, 1998). Ammonia volatilization from surface applied crop residues is reported for various arable crops (De Ruijter *et al.*, 2010; Mannheim *et al.*, 1997; Olsson and Bramstorp, 1994a; b), grass (De Ruijter *et al.*, 2010; Whitehead and Lockyer, 1989; Whitehead *et al.*, 1988) and green manure crops and mulches (De Ruijter *et al.*, 2010; Janzen and McGinn, 1991; Larsson *et al.*, 1998). Ammonia volatilization varies between crop species and meteorological conditions, and in literature values of cumulative ammonia volatilization over 4-10 weeks are found up to 39 to 47% of the N content in ryegrass (Larsson *et al.*, 1998; Whitehead *et al.*, 1988) and 42% of the N content of lentil green manure (Bremer and Vankessel, 1992) .

This paper gives an overview of available literature data on ammonia volatilization from crop residues. From these data, a relation is derived for the ammonia emission depending on the N-content of crop residue. In a following paper, this relationship will be used to assess the contribution of crop residues to the national ammonia emission in the Netherlands.

2. Ammonia volatilization from crop residues - influencing factors

Ammonia may emit from crop residues that remain on the field after harvest. Volatilization of ammonia occurs during decomposition of the crop residues (Marstorp, 1995; Mohr *et al.*, 1998). It generally takes a number of days before first volatilization of ammonia is measured (De Ruijter *et al.*, 2010; Glasener and Palm, 1995; Mannheim *et al.*, 1997). The rate of volatilization is affected by various aspects such as N content of the residues (Whitehead and Lockyer, 1989), air humidity and moisture content of the residues (Whitehead *et al.*, 1988), meteorological conditions as wind speed (Janzen and McGinn, 1991) and temperature (Whitehead *et al.*, 1988) and ambient NH_3 gas concentration (Asman *et al.*, 1998). Furthermore, volatilization is affected by incorporation of the residues into the soil (De Ruijter *et al.*, 2010; Mohr *et al.*, 1998). In this chapter, each aspect is described individually. In Chapter 3, literature data is given and selected based on the various aspects that are described. These data are used to derive an equation to estimate ammonia volatilization from crop residues.

2.1 Ammonia volatilization following protein degradation

Ammonia release from crop residues follows protein degradation in plant tissue. After plant material is cut, protein degradation can result from senescence processes and from decomposition by micro-organisms (Marstorp, 1995). First ammonia volatilization may result from degradation of protein by senescence processes. Microbial growth starts within days and decomposition by micro-organisms will add to the effect of senescence processes or are the cause of ammonia volatilization from dead plant material.

2.1.1 Senescence processes

In attached ryegrass leaves with visual symptoms of senescence and in detached leaves exposed to dark-induced senescence, increased apoplastic and bulk tissue concentrations of NH_4 were found, indicating an increased NH_3 volatilization potential (Mattsson and Schjoerring, 2003). During dark-induced senescence of detached maize leaves, ammonium levels increased and simultaneously protein levels decreased (Chen and Kao, 1996). After cutting green leaves of *Lolium multiflorum*, leaf protein N started to decrease and free amino acid N to increase (Marstorp, 1995). Three days after cutting, the highest free amino acid content was measured and leaf NH_3-N content had started to increase (Figure 2.1, left). Leaf NH_3-N content reached its maximum ten days after cutting. Ammonia volatilization started 6-7 days after cutting when leaf pH had increased to 8.6 (Marstorp, 1995). Start of ammonia volatilization was related to protein-N content of the plant material (Figure 2.1, right), and a higher protein-N content showed earlier volatilization of ammonia. Whitehead and Lockyer (1989) also measured earlier ammonia volatilization from perennial ryegrass herbage with 3.0% N than from grass with 0.9% N (Figure 2.2).
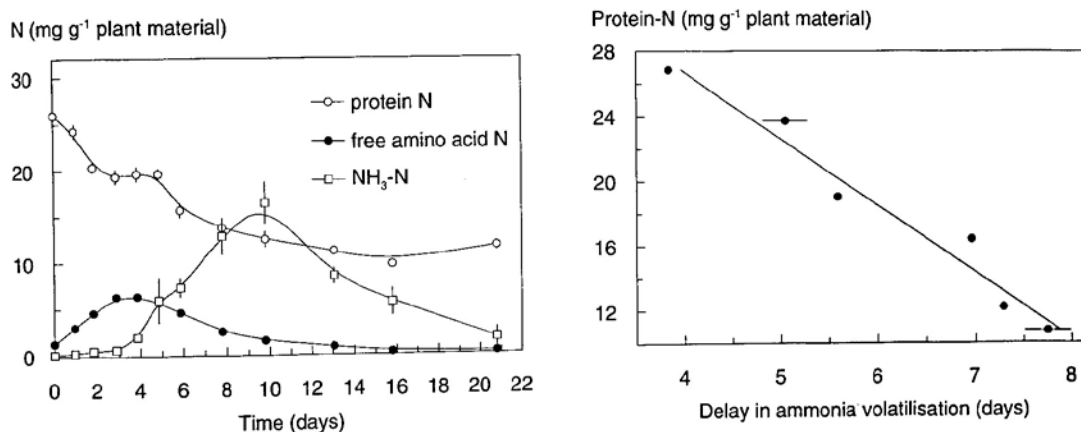
Figure 2.1. *Contents of proteins, free amino acids and ammonia in L. multiflorum leaves during incubation in darkness expressed as a fraction of the original plant dry weight (left) and relationship between the delay in ammonia volatilization and the protein-N content (right). Source: Marstorp, 1995.*
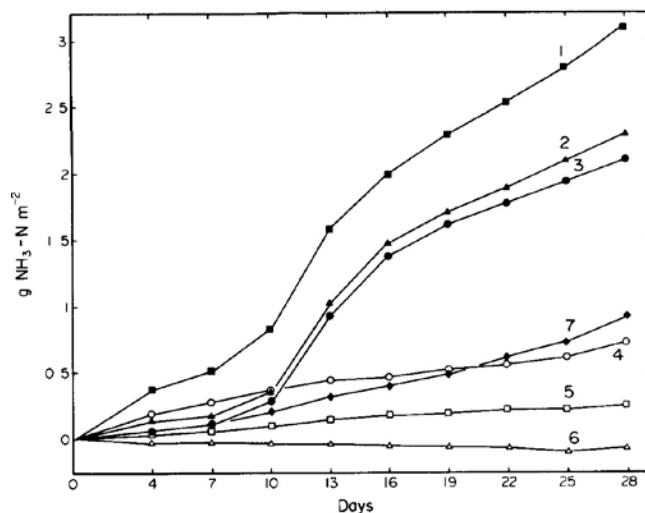
Figure 2.2. *Cumulative volatilization of ammonia-N from decomposing grass herbage in seven wind tunnels (1-3 containing 'high N' grass with 3.0% N, 4-6 'low N' grass with 0.9%N, 7=control. Source: Whitehead and Lockyer, 1989.*

2.1.2 Microbial degradation of plant material

Ammonia volatilization is not only a result of senesce of fresh plant material, but dried plant material applied to the soil surface also shows ammonia volatilization (Janzen and McGinn, 1991). As plant cells of dried material are no longer metabolically active, this ammonia volatilization cannot result from senescence processes and will be caused by microbial degradation (Marstorp, 1995). Fungi were observed within 7 days by Marstorp (1995).
The degradation process in plant cells that have been killed by freezing differs from those in freshly cut plant materials (Marstorp, 1995). Herbage stored frozen did not turn yellow during subsequent decomposition as was the case with fresh herbage where chlorophyll was degraded (Salt, 1965). In the experiments of De Ruijter *et al.* (2010), this effect of freezing on chlorophyll degradation and residue color was also observed (De Ruijter - unpublished information). Salt (1965) observed fungal growth after 4-5 days on fresh grass, and after 2-4 days on grass that was previously stored at -15°C. This may indicate that micro-organisms decompose plant cells that have been killed

by freezing faster than plant cells of fresh plant material. In alfalfa, frost damage lead to increased ammonia volatilization (Dabney and Bouldin, 1985). Frozen fodder radish showed earlier ammonia volatilization than fresh fodder radish (De Ruijter et al., 2010). However, after about two weeks, ammonia volatilization from the fresh fodder radish was higher than from frozen fodder radish and cumulative amounts of ammonia volatilized were higher from fresh fodder radish. Yellow mustard was studied as frozen crop only, but observations may confirm the pattern found with fodder radish: a high initial ammonia volatilization and a relatively low total amount of ammonia volatilized. These observations are too limited to draw conclusions on the effect of freezing on total ammonia volatilization. However, they indicate the role of microbial degradation in ammonia volatilization from crop residues. Either with or without senescence processes, microbial growth starts within days. Decomposition by micro-organisms will add to the ammonia volatilization caused by senescence processes, or can be the major cause of ammonia volatilization from dead plant material.

A build-up of the microbial population may explain the delay between application of crop residues and start of ammonia volatilization. The release of NH_4 by micro-organisms depends on the amount of N that is needed for their own growth and on the amount of N that is available in the plant material. Therefore, ammonia volatilizes earlier from high-N plant material than low-N plant material, as shown by De Ruijter et al. (2010) who found a negative relationship between C/N ratio and ammonia volatilization (Figure 2.3). Differences in ammonia volatilization from crop residues of broccoli and leek between two experimental years were largely explained by differences in composition of the residues between both years, as results of both years fitted in the relationship between the C/N-ratio or N content of the plant material and ammonia volatilization (De Ruijter et al., 2010). In addition to plant composition, the type of micro-organisms involved in decomposing plant material and the fungal/bacterial colony ratios can play a role, as bacteria have a higher N-demand than fungi (Kooijman et al., 2008).
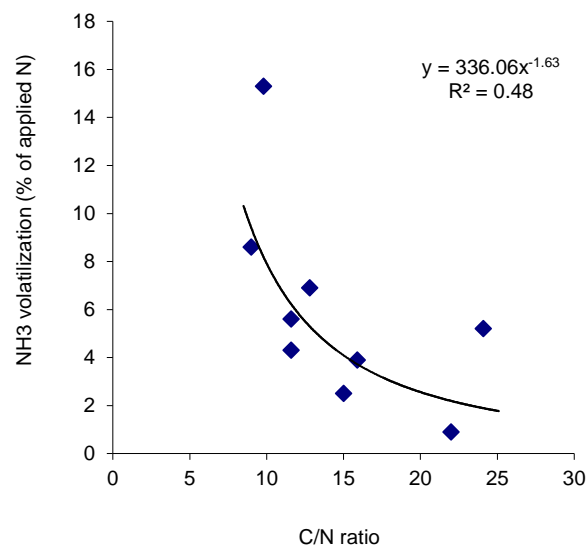
Figure 2.3.   Relation between cumulative ammonia emission after 37 days (expressed as percentage of the applied N) and C/N-ratio.
Source: De Ruijter et al., 2010.

2.1.3   Senescence by herbicides

Termination of a crop by herbicide application (Manderscheid et al., 2005; Mohr et al., 1998) probably increases senescence processes above crop termination by tillage. Ammonia volatilization was earlier with the herbicide application (Figure 2.4) and total ammonia volatilization was slightly increased (Table 2.1). Weed plants also emitted ammonia within a day after application of the herbicide glufosinate (Manderscheid et al., 2005).
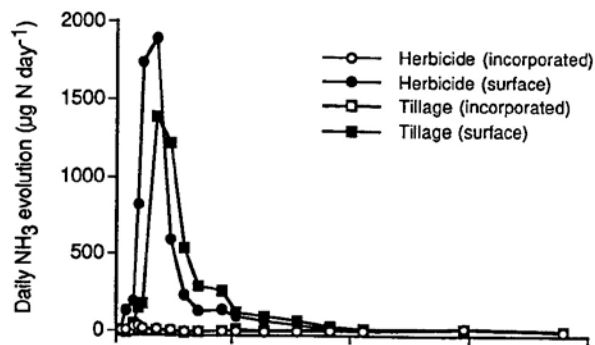
Figure 2.4. Effect of method of alfalfa termination on daily NH₃ evolution. Data for Herbicide (incorporated) equal that of Tillage (incorporated).
Source: Mohr et al., 1998.

Table 2.1. Effect of termination method and residue placement on total NH_3 volatilization from decomposing alfalfa residue (source: Mohr et al., 1998)

Treatment		N in top growth	N content	NH₃ volatilization
Placement	Method	(mg N pot⁻¹)	(%)	(% of surface applied legume N)
Incorporated	Herbicide	130	3.3	0.63
	Tillage	181	3.7	0.45
Surface	Herbicide	130	3.3	11.93
	Tillage	181	3.7	8.02

2.2 Temperature

Temperature affects ammonia volatilization as both senescence processes and growth of micro-organisms depend of temperature. Whitehead *et al.* (1988) found earlier ammonia volatilization at high (20°C) temperature than low (10°C) temperature, but at low temperature volatilization continued over a longer time period. Of the total ammonia volatilization from grass, more than 75% was volatilized within three to four weeks at 20°C whereas this took seven to eight weeks at 10°C (Figure 2.5). At 15.6°C, there was still substantial ammonia volatilization from grass at the end of the experiment after four weeks as the curves of cumulative volatilization were still increasing (Figure 2.2; (Whitehead and Lockyer, 1989). At 25°C, most ammonia was volatilized from lentil green manures after 14 and 17 days (Janzen and McGinn, 1991).
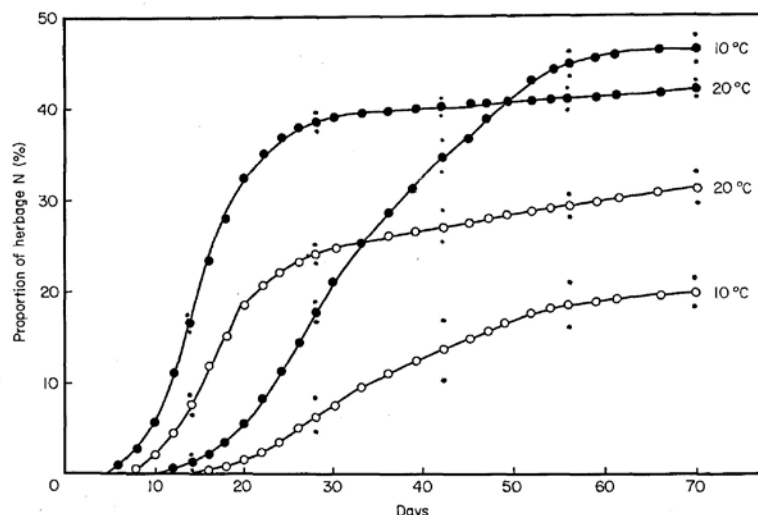
Figure 2.5. *Proportion of the nitrogen in two samples of perennial ryegrass herbage, containing 3.52%*
nitrogen (•–•) or 2.32% nitrogen (o–o), volatilized as ammonia during decomposition
in a moist air stream during 70 d at either 20°C or 10°C. Points represent means of
duplicates; individual values are indicated at five time intervals.
Source: Whitehead et al., 1988.

2.3   Moisture

Moisture strongly affects ammonia volatilization, and compared to moist conditions, negligible volatilization was
found during drying of grass (Whitehead *et al.*, 1988). Whitehead *et al.* (1988) conclude that this has the implication
that hay made in the field under continuous drying conditions is unlikely to release a substantial amount of ammonia
into the atmosphere, and also the short-term wilting for 2-4 days of grass cut for silage is unlikely to result in a
significant release of ammonia, even with some rainfall. However, alternation of drying and rewetting results in an
increase in ammonia volatilization (Janzen and McGinn, 1991), as confirmed by Larsson *et al.* (1998) who found high
emission on a warm day after two days of rainfall, and low emission in the following week during a hot, sunny period
when the plant material of grass and alfalfa mulches dried out.

2.4   Wind speed and ambient gas concentration

Volatilization of NH_3 occurs when the surface concentration is larger than that of the surrounding air (Asman *et al.*,
1998). Both production of NH_3 and export of NH_3 affect this difference in concentration. Important processes are
meteorological processes controlling evaporation and surface temperature, and turbulent and molecular diffusion
in the atmosphere (Sommer *et al.*, 2003). Wind speed is an important factor affecting ammonia volatilization.
From surface applied slurry, ammonia volatilization increased linearly with increasing wind speed and more than
doubled within in the observed range of 0.5-4.5 m s^{-1} (Misselbrook *et al.*, 2005). Increasing wind speed from 2 to
5 m s-1 resulted in an 65% increase in total volatilization for surface applied manure (Huijsmans *et al.*, 2003).
In experiments using volatilization chambers, Janzen and McGinn (1991) demonstrated the effect of air flow rate
on ammonia volatilization. Maximum volatilization could be achieved at air flow rates of 0.3 chamber displacements
min^{-1} or higher.

2.5   Thickness of the layer with residues

Thickness of the layer with residues is positively related to the percentage of the N content that volatilizes as
ammonia. Ribas *et al.* (2010) applied velvet bean residues in quantities of 4, 8 and 12 ton dry matter per hectare,
and measured non-linear increase of ammonia volatilization with increasing residue dosage: 3.3, 4.9 en 8.6 percent

of the N content respectively. These high dosages occur when the crop residues are applied as fertilizer or green mulching in organic farming of horticultural crops (Larsson *et al.*, 1998). The increased ammonia volatilization with high residue dosage may result from relatively little soil contact and delayed transformation of N (Ribas *et al.*, 2010).

2.6 Incorporation into the soil and presence of soil in measurements

Incorporation of crop residues into the soil strongly reduces volatile N losses. Ploughing reduced ammonia volatilization from sugar beet tops by 81 percent, mixing with soil reduced volatilization by 63 percent (Mannheim *et al.*, 1997). De Ruijter *et al.* (2010) found that mixing residues with soil gave negligible ammonia volatilization, whereas volatilization was 5-16 percent of the N content of residues when placed on top of soil. Janzen and McGinn (1991) found that under controlled conditions incorporation of lentil green manure effectively prevented ammonia volatilization, whereas volatilization from surface applied lentil green manure was 5 percent of the N content. Similar results were found by Mohr *et al.* (1998) where incorporation of alfalfa residue essentially eliminated volatile N losses, whereas volatilization from non-incorporated surface applied residues was 8-12 percent of the N content.

Contact between plant material and soil increases ammonia volatilization, as at early stages of decomposition ammonia volatilization was higher from plant material placed on soil surface than from plant material suspended five cm above soil surface (Janzen and McGinn, 1991). This may be caused by more rapid microbial proliferation, but the difference diminished with time and after 56 days both surface placed and suspended plant material had similar ammonia volatilization.
Decomposing plant material probably leaks cell contents, and soil may absorb this and reduce ammonia volatilization. Measurements of ammonia volatilization in glass jars without soil, as carried out by Bremer and Vankessel (1992) and Whitehead *et al.* (1988) may therefore overestimate ammonia volatilization (as discussed in Chapter 3).

2.7 N content

Ammonia volatilization is proportional to the N content in the decomposing plant residue. Bremer and Vankessel (1992) reported volatile N losses of 42, 3.4 and 0.5% of residue N from lentil (*Lens culinaris* L.) green manure, lentil straw and wheat (*Triticum aestivum* L.) straw with N contents of respectively 41, 13 and 9 g/kg dry matter. Volatilization of ammonia was proportionally greater from herbage of perennial ryegrass containing 3.52% nitrogen than from herbage containing 2.32% nitrogen (Whitehead *et al.*, 1988). Herbage containing 2.98% nitrogen lost 10% of its N through ammonia volatilization over a period of 28 days, whereas no volatilization was detected from herbage containing 0.92% N (Whitehead and Lockyer, 1989). De Ruijter *et al.* (2010) showed a regression equation of the relationship between N content and ammonia volatilization. Over a period of 37 days, cumulative ammonia volatilization was negligible from plant material with N concentration below 2 percent, and was 10 percent of the N content of plant material with 4 percent N. This relationship can be explained from decomposition of plant material by micro-organisms. After an initial built up of the microbial population, NH_4^+ that is not needed for their own growth is released and may easily emit as NH_3.

N in plant material is mostly present in organic form, but mineral N can also be found, mainly as nitrate. Within the organic N, a distinction can be made in analysis in soluble and non-soluble organic N. In the relationship between ammonia volatilization and N content, De Ruijter *et al.* (2010) presented only the organic N content as this gave a better relationship than total N. Janzen and McGinn (1991) found differences in ammonia volatilization between field grown and hydroponically grown lentil green manures. They suggest that these differences were not just caused by a difference in total N content, but more importantly by the difference in soluble organic N content. In most literature sources, N content in plant material is given as total N.

3.   Derivation of an equation for estimation of ammonia volatilization from crop residues

Because of the proportionality of ammonia volatilization and N content of decomposing plant material, an equation for estimation of ammonia volatilization from crop residues will be based on this relationship with N content. This equation is based on surface applied residues only, as incorporation of residues almost eliminates ammonia volatilization. Data of ten different studies in literature are used (Table 3.1, Appendix I). These studies consider measured ammonia volatilization over different time periods and at different temperatures. For derivation of the equation, data of total ammonia volatilization at the end of experiments is taken. This relates to farmers' practice on sandy soils in the Netherlands, where most crop residues may remain on the field for several weeks or months when crops are harvested in autumn and the following crop is planted in spring. Shorter field periods occur on clay soil that is plowed before winter, or when crops are harvested early in the season, followed by a succeeding crop. Temperature may affect the rate of ammonia volatilization (Chapter 2.2), but differences in cumulative volatilization were small with long field periods. This supports the use of total ammonia volatilization at the end of experiments.

When all collected literature data of total ammonia volatilization at the end of experiments is plotted against the N content of the plant material used, no clear relationship is found (Figure 3.1). However, a number of data can be removed or adapted, based on plausible reasons and related to the aspects described in chapter 2:
- Within the data of Glasener and Palm (1995; Figure 3.1 green triangles legend 3) a positive relationship between NH3 volatilization and N content is visible, but the N contents reported were low. Presumably, the unit g/kg and % were mistaken; correction of the N content with a factor 10 would give N contents between 14 and 63 g kg-1. As this correction is insecure, and because data are from tropical leguminous crops measured at a temperature of 30°C, these data are omitted.
- Thickness of mulch layer affects ammonia volatilization as can be seen in the results of Ribas *et al.* (2010) at an N content of 27 g kg-1 (legend 8). Of these results, only the data with the lowest ammonia volatilization at a dosage of 35 t ha-1 fresh plant material match the average amounts of residues that remain on the field after crop harvest. Larsson *et al.* (1998) studied ammonia volatilization from plant material applied as mulch layers of 7 or 9 cm thickness. Mulching probably has resulted in increased ammonia volatilization, compared to average amounts of crop residues. This is confirmed by the volatilization from high N grass (39% at N content of 21 g kg-1) which is an outlier (legend 5). Therefore, the data on ammonia volatilization from mulch layers were not included in the regression:
  o 5 - Larsson *et al.* (1998)
  o 8 - Ribas *et al.* (2010)
- Absence of soil during measurements likely overestimates ammonia volatilization. Data from Bremer and Vankessel (1992) and Whitehead *et al.* (1988) show high ammonia volatilization of more than 20%, higher than the majority of measurements. Therefore, the following data were not included in the regression:
  o 1 - Bremer and Vankessel (1992)
  o 10 - Whitehead *et al.* (1988)
  For information on the lower end of the data range, the data point of Bremer and Vankessel (1992) of wheat straw with ammonia volatilization of 0.5% and N content of 9 g kg^{-1} remained in the data set. The volatilization is low despite the likely overestimation of the volatilization.
- De Ruijter *et al.* (2010) measured both organic N and mineral N, and found a better relationship between ammonia volatilization and N content using organic N content only. Therefore, only the organic N content is used for the regression. Excluding the mineral N has a large effect on two data points in Figure 3.1: at NH_3-N volatilization of 11.8% the N content changes from 50.9 to 43.5 g kg^{-1}, and at NH_3-N volatilization of 5.0% the N content changes from 44.5 to 28.0 g kg^{-1}.

The adaptations described above give a relationship between ammonia volatilization and N content of plant residues:

$$NH_3\text{-N volatilization (\% of applied N)} = 0.40 * N \text{ content (g kg}^{-1}\text{ dry matter)} - 5.08 \qquad \text{[Eq. 1]}$$

There is still quite some variation, and the grey lines in Figure 3.2 indicate the 90% confidence band of the regression equation. The 90% prediction band is given by the dotted lines and indicates the interval in which future observations will fall within 90% probability. These ranges can be used to indicate uncertainty around the current regression equation and calculate upper and lower estimates of total ammonia volatilization from crop residues.

Table 3.1.   *Overview of literature on ammonia volatilization from crop residues.*

	Source	Location	Crops	Freshness plant material	Setup	Soil	Temperature	Start exp.	Duration (days)	Moisture
1	Bremer & Van Kessel, 1992	Canada	Green manure, lentil, wheat	Air dried, ground <2 mm	Laboratory, jars	no	20-25 C	n.a.	28	2 g H_2O g^{-1} residue
2	De Ruijter *et al.,* 2010	Netherlands	Broccoli, fodder radish, grass, leek, sugar beet, yellow mustard	Fresh, stored in fridge	Volatilization chambers under rain shelter	yes	-4-14 C	October/November	119	Ambient air, weekly moistened
3	Glasener & Palm, 1996	Tropics, location not reported	Ten tropical legume mulches and green manures	Fresh	Volatilization chambers	yes	30 C	Not reported	21	Daily moistened
4	Janzen & McGinn, 1991	Canada	Lentil green manure	Dry	Volatilization chambers	yes	avg. 25 C	Not reported	14-56	Moistened air, sometimes rewetting residues
5	Larsson *et al.,* 1998	Sweden	Alfalfa, grass	Fresh	Field	yes	10-22 C	June	40	Ambient air, days with rainfall
6	Mannheim *et al.,* 1997	Germany	Beans, potato, sugar beet	Fresh, stored in fridge	Wind tunnels	yes	about 10 C	September	32	Moistened weekly, 3 l m^{-2}
7	Mohr *et al.,* 1998	Canada	Alfalfa	Fresh	Chambers in greenhouse	yes	not reported	April	95	Humidified air
8	Ribas *et al.,* 2010	Brazil	Velvet bean	Fresh	Chambers placed over field	yes	average 21 C	November	30	Average relative humidity 80%
9	Whitehead & Lockyer, 1989	UK	Grass	Fresh	Field, wind tunnels	yes	avg. 15.6 C	July	28	2 liter/m2 every other day
10	Whitehead *et al.,* 1988	UK	Grass	Fresh	Glass jars	no	10 and 20 C	November/December	70	Saturated and dry (8%) air
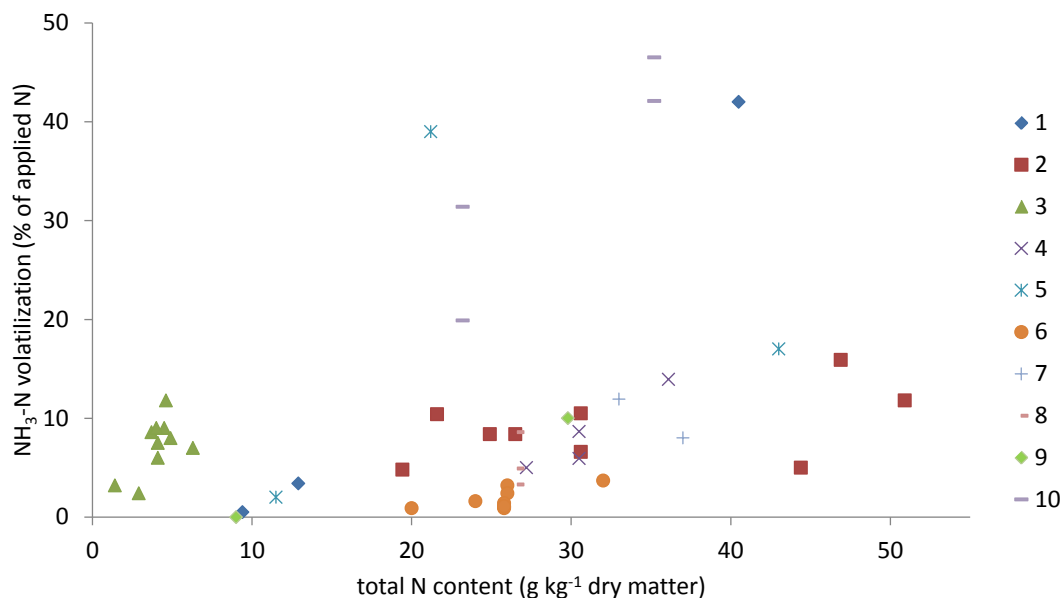
Figure 3.1.   Relationship between ammonia volatilization (% of applied N) at the end of experiments and total N content (g kg^1 dry matter) from references shown in Table 3.1. Only data of surface applied residues are shown.
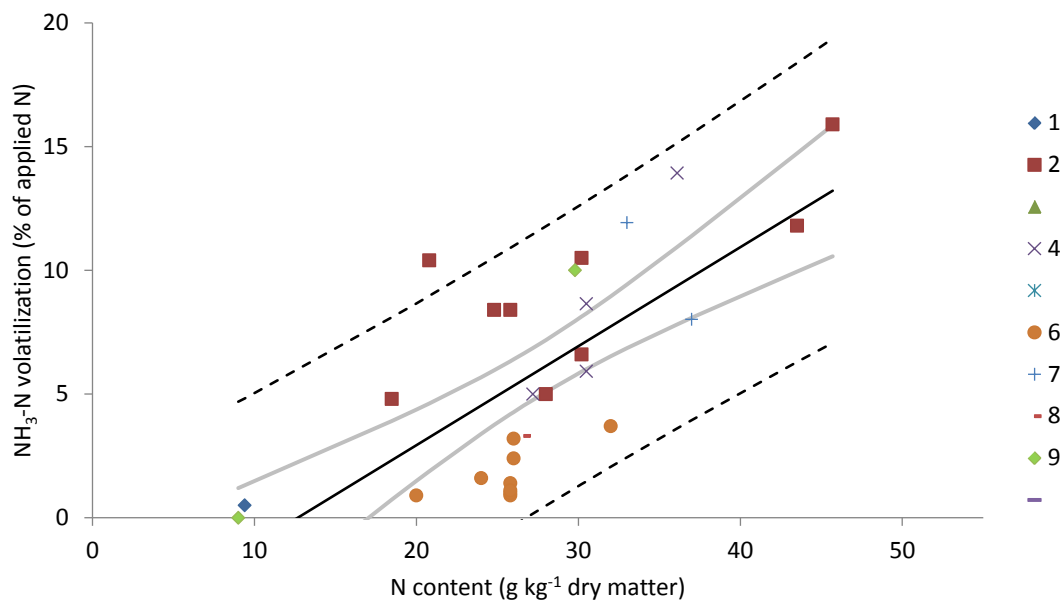
Figure 3.2.   Relationship between ammonia volatilization (% of applied N) at the end of experiments and N content (g kg^1 dry matter) after exclusion of unrepresentative measurements from Figure 3.1, and using organic N content only of reference 2 (see text for explanation). Solid line: regression equation Y = 0.40 * N content - 5.08 (R^2=0.50); Grey lines: 90% confidence band; Dotted lines: 90% prediction band. Note: Scale of vertical axis differs from Figure 3.1.

4. Discussion

Some data were excluded from the derivation of the regression to avoid overestimation because of artificial circumstances in the experiments, such as absence of soil in volatilization chambers or thick layers of residues. Data of the paper of Glasener and Palm (1995) were excluded because the reported N contents were very low. This is likely caused by a mistake in the unit g kg^{-1} or %, but experimental conditions (30°C and tropical crops) were seen not representative for European conditions.
Ammonia may emit from crop residues on the soil surface for several weeks to months. In the experiments of Ribas *et al.* (2010) and Whitehead and Lockyer (1989), ammonia volatilization had not ceased at the end of the experiment. Maximum cumulative NH_3 volatilization may therefore be underestimated in these experiments.
As these experiments comprised only three data points, this has little effect on the regression equation. Therefore, the derived regression equation is valid for crop residues left on the soil surface for a period of time long enough to allow maximum cumulative ammonia volatilization. As temperature affects the rate of volatilization (see Figure 2.5), this can be either within a relative short period at high temperatures, or within a longer period at low temperature.

The derived relationship is valid for residues left on the soil surface, and can be used to estimate the contribution of crop residues to total ammonia volatilization at a national scale. For this, information is required on the amount of residues and the N content. In a following paper, total ammonia volatilization from crop residues will be estimated for the Netherlands, using the regression equation, national statistics on crop cultivation, and literature and expert knowledge on the amount and N content of residues and timing of incorporation.

5.   Conclusion

The degree of ammonia volatilization is related to the N content of plant residues by the following regression equation:

$$NH_3\text{-N volatilization (\% of applied N)} = 0.40 * N \text{ content (g kg}^{-1} \text{ dry matter)} - 5.08 \qquad (R^2 = 0.50)$$

This relation accounts for crop residues left on soil surface as absence of soil in the experimental setup may overestimate ammonia volatilization. Mulching, or application of a thick layer of crop residues is not taken into account because the thick layers increase ammonia volatilization compared to application of average amounts of crop residues on soil surface.

References

Asman, W.A.H., M.A. Sutton & J.K. Schjorring, 1998.
  Ammonia: emission, atmospheric transport and deposition. New Phytol 139, 27-48.
Bremer, E. & C. Vankessel, 1992.
  Plant-available nitrogen from lentil and wheat residues during a subsequent growing-season. Soil Science Society of America Journal 56, 1155-1160.
Chen, S.J. & C.H. Kao, 1996.
  Ammonium accumulation in relation to senescence of detached maize leaves. Bot. Bul. Acad. Sin. 37, 255-259.
Dabney, S.M. & D.R. Bouldin, 1985.
  Fluxes of ammonia over an alfalfa field. Agronomy Journal 77, 572-578.
De Ruijter, F.J., J.F.M. Huijsmans & B. Rutgers, 2010.
  Ammonia volatilization from crop residues and frozen green manure crops. Atmos. Environ. 44, 3362-3368.
Denmead, O.T., R. Nulsen & G.W. Thurtell, 1978.
  Ammonia exchange over a corn crop. Soil Science Society of America Journal 42, 840-842.
EC, 2001.
  Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants. Official Journal L 309, 22 (accessed 27.11.01). European Communities, Brussels.
Farquhar, G.D., P.M. Firth, R. Wetselaar & B. Weir, 1980.
  On the gaseous exchange of ammonia between leaves and the environment - determination of the ammonia compensation point. Plant Physiol. 66, 710-714.
Glasener, K.M. & C.A. Palm, 1995.
  Ammonia volatilization from tropical legume mulches and green manures on unlimed and limed soils. Plant Soil 177, 33-41.
Harper, L.A., D.W. Bussink, H.G. vanderMeer & W.J. Corre, 1996.
  Ammonia transport in a temperate grassland .1. Seasonal transport in relation to soil fertility and crop management. Agronomy Journal 88, 614-621.
Harper, L.A., R.R. Sharpe, G.W. Langdale & J.E. Giddens, 1987.
  Nitrogen cycling in a wheat crop - soil, plant, and aerial nitrogen transport. Agronomy Journal 79, 965-973.
Hooker, M.L., D.H. Sander, G.A. Peterson & L.A. Daigger, 1980.
  Gaseous-N losses from winter-wheat. Agronomy Journal 72, 789-792.
Huijsmans, J.F.M., J.M.G. Hol & G.D. Vermeulen, 2003.
  Effect of application method, manure characteristics, weather and field conditions on ammonia volatilization from manure applied to arable land. Atmos. Environ. 37, 3669-3680.
Hutchinson, G.L., R.J. Millington & D.B. Peters, 1972.
  Atmospheric ammonia - absorption by plant leaves. Science 175, 771-775.
Janzen, H.H. & S.M. McGinn, 1991.
  Volatile Loss of Nitrogen During Decomposition of Legume Green Manure. Soil Biol. Biochem. 23, 291-297.
Kooijman, A.M., M.M. Kooijman-Schouten & G.B. Martinez-Hernandez, 2008.
  Alternative strategies to sustain N-fertility in acid and calcaric beech forests: Low microbial N-demand versus high biological activity. Basic Appl. Ecol. 9, 410-421.
Larsson, L., M. Ferm, A. KasimirKlemedtsson & L. Klemedtsson, 1998.
  Ammonia and nitrous oxide emissions from grass and alfalfa mulches. Nutr Cycl Agroecosyst 51, 41-46.
Manderscheid, R., S. Schaaf, M. Mattsson & J.K. Schjoerring, 2005.
  Glufosinate treatment of weeds results in ammonia emission by plants. Agr Ecosyst Environ 109, 129-140.
Mannheim, T., J. Braschkat & H. Marschner, 1997.
  Ammonia emissions from senescing plants and during decomposition of crop residues. Z Pflanz Bodenk 160, 125-132.

18

Marstorp, H. 1995.
    Influence of protein degradation and protein content in cut Lolium multiflorum leaves on the delay in ammonia
    volatilisation. Swed. J. Agric. Res. 25, 179-183.
Mattsson, M. & J.K. Schjoerring, 2003.
    Senescence-induced changes in apoplastic and bulk tissue ammonia dconcentrations of ryegrass leaves. New
    Phytol 160, 489-499.
Milford, C., M.R. Theobald, E. Nemitz, K.J. Hargreaves, L. Horvath, J. Raso, U. Dammgen, A. Neftel, S.K. Jones,
    A. Hensen, B. Loubet, P. Cellier & M.A. Sutton, 2009.
    Ammonia fluxes in relation to cutting and fertilization of an intensively managed grassland derived from
    an inter-comparison of gradient measurements. Biogeosciences 6, 819-834.
Misselbrook, T.H., F.A. Nicholson & B.J. Chambers, 2005.
    Predicting ammonia losses following the application of livestock manure to land. Bioresource Technology 96,
    159-168.
Mohr, R.M., H.H. Janzen & M.H. Entz, 1998.
    Nitrogen dynamics under greenhouse conditions as influenced by method of alfalfa termination. 1. Volatile N
    losses. Can J Soil Sci 78, 253-259.
Nemitz, E., M.A. Sutton, A. Gut, R. San Jose, S. Husted & J.K. Schjoerring, 2000.
    Sources and sinks of ammonia within an oilseed rape canopy. Agr Forest Meteorol 105, 385-404.
Odeen, W.A. & L.K. Porter, 1986.
    Continuous-flow system for collecting volatile ammonia and amines from senescing winter-wheat.
    Agronomy Journal 78, 746-749.
Olsson, R. & A. Bramstorp, 1994a.
    Fate of nitrogen from sugar-beet tops. Institut International de Recherches Betteravieres, Bruxelles 1994,
    189-212.
Olsson, R. & A. Bramstorp, 1994b.
    Where does nitrogen from sugar-beet leaves and from sugar-beet crown remain?. Zuckerruebe (Germany).
    (1994) 43, 310-313.
Ribas, R.G.T., R.H.S. Santos, R.G. Siqueira, E.R. Diniz, L.A. Peternelli & G.B. de Freitas, 2010.
    Decomposition, release and volatilization of nitrogen from velvet bean (Mucuna cinerea) residues.
    Cienc. Agrotec. 34, 878-885.
Salt, P.D., 1965.
    An apparatus for measuring losses of ammonia from decomposing plant materials. Chem. Ind., 461-462.
Schjoerring, J.K. & M. Mattsson, 2001.
    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.
Sommer, S.G., S. GenermontS, P. Cellier, N.J. Hutchings, J.E. Olesen & T. Morvan, 2003.
    Processes controlling ammonia emission from livestock slurry in the field. Eur J Agron 19, 465-486.
Sutton, M.A., E. Nemitz, C. Milford, C. Campbell, J.W. Erisman, A. Hensen, P. Cellier, M. David, B. Loubet,
    E. Personne, J.K. Schjoerring, M. Mattsson, J.R. Dorsey, M.W. Gallagher, L. Horvath, T. Weidinger,
    R. Meszaros, U. Dammgen, A. Neftel, B. Herrmann, B.E. Lehman, C. Flechard & J. Burkhardt, 2009.
    Dynamics of ammonia exchange with cut grassland: synthesis of results and conclusions of the GRAMINAE
    Integrated Experiment. Biogeosciences 6, 2907-2934.
Van Pul, W.A.J., M.M.P. Van den Broek, H. Volten, A. Van der Meulen, A.J.C. Berkhout, K.W. Van der Hoek,
    R.J. Wichink Kruit, J.F.M. Huijsmans, J.A. Van Jaarsveld, B.J. De Haan & R.B.A. Koelemeijer, 2008.
    The ammonia gap: research and interpretation [in Dutch: Het ammoniakgat: onderzoek en duiding].
    Bilthoven, RIVM, rapport 680150002.
Velthof, G.L., C. van Bruggen, C.M. Groenestein, B.J. De Haan, M.W. Hoogeveen & J.F.M. Huijsmans, 2009.
    Methodology to calculate ammonia emissions by Dutch agriculture [In Dutch: Methodiek voor berekening
    van ammoniakemissie uit de landbouw in Nederland]. Wageningen, Statutory Research Tasks Unit for
    Nature & the Environment, WOt Report No. 70.
Velthof, G.L., C. Van Bruggen, C.M. Groenestein, B.J. De Haan, M.W. Hoogeveen & J.F.M. Huijsmans, 2011.
    A model for inventory of ammonia emissions from agriculture in the Netherlands. Atmospheric Environment
    46: 248-255.

Whitehead, D.C. & D.R. Lockyer, 1989.

    Decomposing Grass Herbage as a Source of Ammonia in the Atmosphere. Atmos. Environ. 23, 1867-1869.

Whitehead, D.C., D.R. Lockyer & N. Raistrick, 1988.

    The Volatilization of Ammonia from Perennial Ryegrass During Decomposition, Drying and Induced Senescence. Ann. Bot. 61, 567-571.

Appendix I.

Literature data on ammonia volatilization from surface applied crop residues

	Applied residue						NH3-volatilization (% of applied N) at different days after application																	
	fresh (t/ha)	dry (t/ha)	N (kg/ha)	C/N	Ntot (g/kg)	N-org (g/kg)	7	14	16	18	21	23	25	28	30	37	43	51	57	65	72	79	93	119
1. Bremer & Van Kessel, 1992																								
lentil green manure				10.3	41		20.7							42										
lentil straw				31	13		0.8							3.4										
wheat straw				43.1	9		0.2							0.5										
2. De Ruijter et al., 2010																								
Broccoli (leaves)	42	5.9	300	9	50.9	43.5	0	0.1			1.5			4.8		8.6								11.8
Leek	59	6.4	170	13	26.5	25.8	0.4	1.5			3.2			5.4		6.9								8.4
Broccoli (leaves+stem)	42	6.0	116	22	19.4	18.5	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.7	0.9	0.9	0.9	1.0	1.2	1.9	2.7	3.9	4.8
Leek	59	5.7	122	24	21.6	20.8	0.1	0.7	1.0	1.5	2.2	2.7	3.2	4.0	4.4	5.2	5.7	6.4	7.1	7.8	8.5	9.2	9.9	10.4
Sugar beet tops	42	8.0	200	15	24.9	24.8	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.5	0.8	2.5	3.2	3.7	4.2	4.7	5.5	6.3	7.1	8.4
Grass	17	2.5	117	10	46.9	45.7	0.1	2.5	5.3	8.5	10.8	11.9	12.8	14.0	14.5	15.3	15.5	15.6	15.6	15.6	15.7	15.7	15.8	15.9
Fodder radish-fresh	42	4.2	128	12	30.6	30.2	0.0	0.1	0.2	0.5	1.1	1.6	2.2	3.2	3.7	5.6	6.7	7.4	8.3	9.1	9.9	10.2	10.4	10.5
Fodder radish-frozen	42	4.2	128	12	30.6	30.2	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.7	2.1	4.3	5.1	5.5	6.1	6.3	6.4	6.5	6.5	6.6
Yellow mustard-frozen	42	3.6	159	16	44.4	28	0.5	1.8	2.3	2.7	3.1	3.2	3.4	3.5	3.6	3.9	4.2	4.3	4.5	4.6	4.6	4.7	4.8	5
3. Glasener & Palm, 1996																								
Desmodium valifolium	10			14.5	2.9						2.4													
Oryza sativa	10			27.5	1.4						3.2													
Canavaliaensiformis	10			10.1	3.7						8.6													
Crotolaria juncea	10			7.4	6.3						7.0													
Centrosema macrocarpum	10			9.9	4.6						11.8													
Tephrosia spp.	10			11.4	4.1						6.0													
Mucuna cochichinensis	10			10.1	4.5						9.0													
Macroptilium atropurpureum	10			9.2	4.9						8.0													
Stylosanthesquianensis	10			10.8	4.0						9.0													
Arachis hypoqaea	10			10.8	4.1						7.5													

Applied residue	fresh (t/ha)	dry (t/ha)	N (kg/ha)	C/N	Ntot (g/kg)	NH3-volatilization (% of applied N) at different days after application							
						14	17	18	28	32	40	56	95
4. Janzen & McGinn, 1991													
lentil green manure		?			27.2							5.0	
lentil green manure		?			30.5				3.6				
lentil green manure		?			30.5	8.7	5.9						
lentil green manure		?			36.1	13.9							
5. Larsson *et al.*, 1998													
low N grass	158	30.3	348	36	11.5						2		
high N grass	158	22.8	482	21	21.2						39		
alfalfa	158	23.2	1006	11	43						17		
6. Mannheim *et al.*, 1997													
Bean	20.2		335		20					0.9			
Sugar beet	43.6		302		26					3.2			
Sugar beet	87.1		358		26					2.4			
Potato	41.3		344		32					3.7			
Sugar beet	76.6		281		24					1.6			
Sugar beet 15.9°C	98.8		438		25.8					1.4			
Sugar beet 15.9°C	114.8		510		25.8					0.9			
Sugar beet 10.6°C	106.9		475		25.8					1			
Sugar beet 10.6°C	117		518		25.8					1.1			
7. Mohr *et al.*, 1998 (alfalfa)													
herbicide		>			33			10					11.9
tillage		?			37			6					8.02

	Applied residue					NH3-volatilization (% of applied N) at different days after application							
	fresh (t/ha)	dry (t/ha)	N (kg/ha)	C/N	Ntot (g/kg)	7	16	17	28	30	33	37	70
8. Ribas *et al.*, 2010													
green manure		4	106.6	16.8	26.6					3.3			
green manure		8	213	16.8	26.6					4.9			
green manure		12	320	16.8	26.6					8.6			
9. Whitehead & Lockyer, 1989													
low N grass	40	9.3	85.4		9				0				
high N grass	41	5.3	157.9		29.8				10				
10. Whitehead, Lockyer & Raistrick, 1988													
high N grass - 20 C					35.2	2						39.5	42.1
high N grass - 10 C					35.2		2	25			25	28	46.5
low N grass -20 C					23.2							26	31.4
low N grass -10 C					23.2							11	19.9