Applied Model for Estimating Potential Ammonia Loss from Surface Applied Urea

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Abstract

Ammonia loss from urea fertilizer is a major concern to farmers all over the world. Various environmental factors such as temperature, soil water content, wind speed, pH, rainfall, relative humidity, cation exchange capacity (CEC), soil organic matter and others influence ammonia volatilization loss. The objective of this work was to establish a model for estimating ammonia loss utilizing published data. Also, using current day inputs (temperature, wind speed, and known soil pH) estimates could relate risk to producers considering surface applications of urea fertilizer without incorporation. Linear models for soil pH and ammonia loss, ambient temperature and ammonia loss, and wind speed and ammonia loss were determined based on more than 40 published articles. Final estimates of ammonia loss employed an additive effects model using inputs for pH, temperature, and wind speed. Web access to this model can be located at www.nue.okstate.edu/ammonia_loss.htm.

Keywords: Urea, urea hydrolysis, ammonia loss, ammonia volatilization

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Introduction

A growing world population and increased food demand have led to increased demands for fertilizer. As a result, greater pressure on agricultural production has ensued, which in turn has resulted in an overall increase in fertilizer use. The Food and Agricultural Organization (FAO) projected that between 2007/2008 and 2011/2012 the global demand for nitrogen fertilizer would have increased by 1.4%, which equals an increase of 7.3 million metric tons (Mt) for a total of more than 105 million tons (FAO, 2008).

When discussing the increased demand for fertilizers, the contribution of urea cannot be underestimated. Urea is by far the most widely used fertilizer in crop production (Soh 2001, Stumpe et al., 1984). The International Fertilizer Industry Association (IFA) projected the global urea demand to grow from 148.9 Mt in 2010 to 155.3 Mt in 2011 (Heffer and Prud'homme, 2010). The United States of America (US) and Canada represent approximately 20% of the global urea market, while urea comprises 30% of US nitrogen fertilizer use (Glibert et al., 2006)

The growth in fertilizer use for food production has also increased fears of environmental pollution. If nitrogen is applied in quantities exceeding the amount used by the crop, it can be lost to the environment. One of the disadvantages of urea fertilizer is that when surface applied it can be lost to the environment as gaseous ammonia (Stumpe et al., 1984) affecting the nitrogen use efficiency and subsequently crop yields. Global ammonia emissions have been estimated to be around 50 million tons of nitrogen (N) per year (Asman 1992; Shlesinger and Hartley 1992; Bouwman et al., 1997). Ammonia emission in Europe alone has been estimated to be approximately 4.5 million tons N per year, mainly coming from animal husbandry and application of synthetic fertilizers (Asman 1992; ECETOC 1994).

Literature reports ammonia emission of 7% (Goebes et al., 2003; Roe et al., 1998) and 9.5% (Goebes at al., 2003; Battye et al., 1994) for the US, expressed as percentages of the total global ammonia emission.

When urea is applied to a soil with it is almost immediately hydrolyzed. The hydrolysis of urea produces ammonium carbonate $(NH_4)_2CO_3.H_2O$ which breaks down to carbon dioxide (CO_2) and ammonia (NH_3), producing a high soil pH and ammonia loss (Eriksen and Kjeldby 1987; Fenn and Kissel 1973). Especially in the North Central region of the United States, loss of nitrogen as ammonia seems to be a major concern since 50% of the nitrogen fertilizer used is applied as urea or urea containing products (Oberle and Bundy 1987; Hargett and Berry 1985).

The subject of ammonia volatilization as it relates to environmental factors has also been extensively studied and the results have been presented in numerous reports. The objective of this paper is to summarize some of the results of these studies specifically dealing with ammonia volatilization from surface applied urea and to use this published data for the generation of an overall model that farmers can use to calculate ammonia loss.

Review of literature

Loss as a function of pH

There is general agreement among scientists that ammonia loss increases with increasing soil pH.

A high soil pH combined with high temperatures causes higher volatilization rates resulting from higher concentrations of NH_3 dissolved in soil water. When the pH rises above 7.5 there is a significant increase of dissolved NH_3 in the soil solution (Jones et al., 2007).

Ernst and Massey (1960) reported increased losses of ammonia with increasing temperature and pH from urea applied to a Kentucky soil. Meyer et al. (1961) found that losses of urea and urea containing products as ammonia are greatest on neutral to alkaline soils under conditions of a light rainfall. Volatilization can also occur on acidic soils because of the alkaline conditions that develop in the immediate proximity of the urea granules as urea dissolves and hydrolyses (Stevens et al., 1989; Volk 1959).

Loss as a function of relative humidity

Research in Denmark has shown that accumulated loss of ammonia from urea ranged from 18 to 30% of the total applied N when the humidity was sufficient for hydrolysis (Sommer and Jensen, 1994). Reynolds and Wolf (1987) note that the influence of relative air humidity between 25 and 85% was insignificant at a water potential of -0.033 MPa. They found substantial ammonia volatilization at a relative humidity of 85% and a soil water potential of <-1.5 MPa, indicating that the effect of relative humidity was greater at limiting soil water potential. In a study addressing the recovery of nitrogen by corn from both solid and liquid fertilizers Terman et al. (1968) found lower ammonia volatilization losses at a relative humidity of 70% as compared to a relative humidity of 100%. On the contrary, another study shows a lower cumulative ammonia loss at 0 and 100% relative humidity as compared to relative humidity treatments of 87.5± 2.5% and 52.5± 2.5% (Ernst and Massey, 1960).

Loss as a function of moisture content

Urea starts breaking down as soon as it is applied to a soil surface. As the moisture content of a dry soil increases, more urea is converted to ammonium carbonate. This compound may then remain near the soil surface until sufficient moisture is present to carry it deeper into the soil and thereby preventing further loss through volatilization (Trierweiler and Bishop, 1983).

When urea is applied to a moist soil surface it reacts with water and the urease enzyme and is rapidly converted to ammonium. Stumpe et al. (1984) showed that decreasing soil moisture content from 0.30 to 0.23 kg kg^{-1} caused a significant reduction in the amount of ammonia lost from the soil. Denmead et al. (1978) found ammonia loss rates of as much as 27.6 g N ha^{-1} $hour^{-1}$ from the plant soil system when the soil surface was moist.

Kresge and Satchell (1960) found that most volatilization from urea applied to a fine sandy loam and a silt loam would occur at 20% moisture and when soils were drying out from a moisture content near field capacity.

Chin and Kroontje (1963) found less volatilization loss from urea applied to wet soils and attributed this to a larger water surface that is available for ammonia adsorption.

In two greenhouse experiments Stumpe and Mas Abdel (1986) found that losses of urea-N increased with increased topsoil moisture at fertilizer application and with decreased depth of precipitation after fertilizer application. This same study shows an increase in urea-N loss of 5 and 13% when applied to wet rather than dry Houston and Savannah soils respectively (Stumpe and Mas Abdel, 1986).

Loss as a function of wind speed

Various studies reviewed for this paper agree that increasing wind speed near the soil surface favors ammonia volatilization (Watkins et al. 1972; Bouwmeester and Vlek 1981; Fillery et al., 1984)

A study on ammonia loss from urea applied to forest soils showed an increase in ammonia loss with increased wind speed ranging from 0.0004 to 0.01 km hr^{-1}(Watkins et al., 1972). Bouwmeester et al. (1985) observed from a wind tunnel experiment that increasing wind velocity from 6.1 to 12.2 km hr^{-1} resulted in a reduction in ammonia loss from 19 to 7.5%.

Data presented by Fillery et al. (1984) showed a linear increase in NH_3 loss with increased wind speed and partial pressure of NH_3 in floodwaters of a rice field. These findings are similar to what Bouwmeester and Vlek (1981) found in a study with wind tunnels simulating a floodwater system, where ammonia loss was found to increase linearly with wind speed.

Nathan and Malzer (1994) observed that the rate of NH_3 volatilization from manure and urea was highest during 1200 and 1800 hours and lowest between 2400 and 600 hours. This fluctuation corresponded closely to the daily fluctuations in soil temperature, soil water potential and wind speed.

Loss as function of temperature

It is well known that temperature influences many biochemical reactions, including urease production and activity. Hargrove (1988) lists a number of ways in which temperature affects ammonia loss. Several works seem to be in agreement that ammonia volatilization increases with increasing temperature.

In a laboratory experiment Watkins et al. (1972) found increasing NH_3 losses from urea applied to forest floors, with increasing temperature. In a laboratory study where urea was surface-applied to a Dickson silt loam soil, Ernst and Massey (1960) report that each 8 degrees Celsius increase in temperature produced a significant increase in volatilized ammonia. In a comprehensive report Volk (1961) notes that temperatures of 7 °C and below retards urease production and activity but as temperatures rise above 15 °C ammonia volatilization greatly increases.

Research in Brazil has shown that volatilization rates and cumulative losses were greatest in those years with low volumes of precipitation and high average temperatures (Fontoura and Bayer, 2010).

Another study conducted in Canada observed an increase in ammonia loss from surface applied urea from spring to summer, with air temperature as the most influential factor (Kunelius et al., 1987).

However, the findings of Meyer et al. (1961) seems to contradict the notion that ammonia volatilization increases as temperature increases as this work reports higher losses from urea at a lower temperature in a greenhouse experiment. This was attributed to less microbial activity at lower temperatures reducing the conversion rate of ammonium to nitrate, leading to a buildup of ammonium in excess of the soil's adsorption capacity leaving more of this compound available for loss through evaporation.

Loss as affected by plant cover/residue

Several workers describe the significance of plant residues on the soil surface in relationship to ammonia volatilization by indicating that plants and plant residues act as a source of urease and as a medium through which ammonia must pass (Freney and Black 1988, Nelson et al., 1980; Frankenberger and Tabatabai 1982; Torello and Wehner 1983; Vallis and Gardener 1984; Tomar et al., 1985; Bacon et al., 1986).

Kresge and Satchell (1960) found that heavy and medium plant cover significantly reduced ammonia loss from urea, applied at a rate of 112 kg N ha^{-1}. A study looking at ammonia loss from fields covered with sugarcane residue showed that the cane residue had no capacity to retain ammonia. This study found rather that the cycle of moistening and evaporation resulted in losses ranging from 30% to 40% over a period of 6 weeks (Freney et al., 1992). In a study conducted when UAN was applied to straw residue McInnes et al. (1986) found that NH_3 loss peaked around noon, as straw temperatures were rising to a maximum, straw-water content was decreasing and wind velocity was high. Keller and Mengel (1986) found that 50.9 kg (30.3%) of the total of 168 kg ha^{-1} of urea applied to no- till corn was lost as ammonia. Other research revealed losses ranging from 27-46% of urea applied to mineral soils covered with forest floor material compared to losses ranging from 6-30% for urea applied to bare mineral soil (Watkins et al., 1972).Tomar et al. (1985) found an 11% increase in ammonia loss from urea solutions applied to soil covered with 4600 kg ha^{-1} hay as compared to soil not covered with hay.

Loss as affected by rainfall

Several studies have recognized the significance of rainfall and its effect on ammonia volatilization (Craig and Wollum II 1982; McInnes et al., 1986; Oberle and Bundy 1987; Stevens et al., 1989).

Stevens et al. (1989) reported that interaction between rainfall and the ammonia volatilization process will largely affect the efficiency of urea when applied to acidic soil. Research in the Netherlands has shown that 5 mm of precipitation in the two days following urea application is needed to prevent ammonia volatilization (Stevens et al., 1989; Van Burg et al., 1982). Oberle and Bundy (1987) found that rainfall following N application significantly decreased ammonia volatilization.

Craig and Wollum II (1982) found that light rainfall providing just enough moisture for hydrolysis, but not enough to leach urea resulted in the greatest NH_3 losses.

A study conducted by McInnes et al. (1986) has shown that 25 to 30% of urea would be hydrolyzed if applied immediately following rainfall, but that hydrolysis would be nonexistent when the water content of the soil surface reached “air dryness” and ammonia loss would be around 4%.

Prasertak et al. (2001) reports limited initial loss of ammonia from urea applied to a dry soil until 3 mm, 1.2 mm and 2.4 mm of rainfall within 2, 3 and 4 days after application respectively resulted in a more rapid loss of ammonia.

Numerous studies dealing with the loss of ammonia from surface applied urea have been conducted. The complexity of the interactions between environmental factors such as soil pH, soil temperature, relative humidity, rainfall, wind speed and others are beyond the scope of this paper. Nonetheless, ammonia loss is clearly an issue for surface applications of urea, demonstrated in the range of differing results found in the literature. However, the numerous research papers cited here provide sufficient evidence to conclude that ammonia volatilization from surface applied urea increases with increasing pH, increasing temperature and wind speed.

Materials and Methods

A total of 159 records for ammonia loss were found in agricultural literature, collected from 1960 to 2010. From a combined 25 different references, relative humidity, surface moisture, surface air temperature, wind speed, presence/absence of surface residue, and ammonia volatilization losses were recorded. For the research journal articles included in this work, each paper was unique in that they collected different types of data. However, and fortunately for this study, most articles documenting ammonia loss, included data for wind speed, soil pH, and surface temperature. Because of this, wind speed, soil pH, and surface temperature were the input variables chosen that would be used for predicting ammonia loss over a large area, and range of production conditions. Also, many states now have on-line weather sites where live wind speed and surface temperature can be accessed. For each journal article where a record was entered, data collected was converted to metric units if and when reporting was in another standard. Some journal articles included estimates of ammonia loss for multiple locations, and or years. In each case, by-year, by-location data was considered to be unique. Once the complete data set was compiled with 43 site-years, linear models from the combined data were generated for ammonia loss versus soil pH, ammonia loss versus wind speed, and ammonia loss versus surface air temperature (Table 1). Although the coefficients of determination (r^2) were not high for any of the 3 linear models, intercept and slope components were highly significant for all three (Table 1). Multiple regression was also evaluated using data for all independent variables and where ammonia loss was also determined. However, sufficient data was not present that would allow sufficient degrees of freedom in the model to properly test soil pH, wind loss, and temperature. These results are thus not reported.

Slopes for the three linear regression equations (AL versus air temperature, AL versus wind speed, AL versus soil pH) were subsequently evaluated. The variable where the largest percent change in ammonia loss over the range of data included was then selected, and that was used as a base model (soil pH, Table 1). To arrive at an overall equation that included all 3 (air temperature, wind speed, soil pH), excluding intercepts, effects were considered to be additive. As a result, the final estimate of ammonia loss used the base model, with added slope components for wind speed and air temperature.

The resulting model follows;

$AL = b0_{pH} + b1_{pH}(pH)) + b1_{ws}(WS) + b1_{AT}(AT)$

Where AL is ammonia loss, $b0_{pH}$ is the intercept from the linear model of AL and pH, $b1_{pH}$ is the slope from the linear model of AL and pH, $b1_{ws}$ is the slope from the linear model of AL and wind speed, and $b1_{AT}$ is the slope from the linear model of AL and air temperature.

The final coefficients were, -40.7, 8.43, 3.85, and 0.33 for $b0_{pH}$, $b1_{pH,}$ $b1_{ws,}$ and $b1_{AT,}$ respectively.

To use the "Ammonia Loss Calculator" (http://nue.okstate.edu/N_Fertilizers/Urea.htm) knowledge of the presence and/or absence of surface residues is also needed.

Conclusions

Because urea is the most popular commercial fertilizer used today, ammonia loss from this N source remains important. Increasing food demand and environmental concerns have made it necessary for producers worldwide to more efficiently manage N resources. The need for achieving higher yields with existing N sources, both indigenous and applied, calls for innovative nutrient management tools for producers worldwide.

Numerous laboratory, field and greenhouse studies have been carried out to measure ammonia loss from urea and urea containing products. The overall trend that can be derived from published research cited here is that that ammonia volatilization from surface applied urea increases with increasing pH, increasing temperature and higher wind speeds. It is expected therefore that when fertilizer urea is applied on high pH soils, during warm humid weather and under windy conditions, ammonia losses will be high. Furthermore, what the literature review clearly showed was that temperature, pH, and wind speed were the most common variables being used to estimate NH3 loss. This is not to say that the other variables measured in these studies were not important, but rather that these three contributed more towards ending up with accurate models for estimating NH3 losses in agriculture.

Using combined published research, a composite algorithm was developed to provide estimates of potential ammonia losses based on soil pH, wind speed, and air temperature. These variables are available for site specific recommendations all over the world, and that can be input into an on-line calculator (http://nue.okstate.edu/N_Fertilizers/Urea.htm). Real time estimates of ammonia loss from surface applied urea will assist in making better fertilizer management decisions, and potentially avoiding days where ammonia loss from surface applied urea is expected.

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Table 1. Intercept, slope, coefficient of determination (r^2) and number of observations for ammonia loss versus temperature, soil pH, and wind speed, from 25 independent research articles collected from 1960 to 2010.

Equation	Intercept	Slope	r^2	n
Ammonia loss and temperature, C	18.21**	0.33*	0.04	88
Ammonia loss and wind speed, m/sec	9.74*	3.85**	0.27	28
Ammonia loss and soil pH	-40.77*	8.43**	0.18	25

*, **, model component significant at the 0.05, and 0.01 probability level, respectively.