Current and Future Emissions of Ammonia in China

Zbigniew Klimont
International Institute for Applied Systems Analysis (IIASA), 2361 Laxenburg, Austria
klimont@iiasa.ac.at

ABSTRACT

Ammonia emission inventory for 1990 and 1995 as well as scenarios up to 2030 are presented for China. Emissions are estimated on a provincial level using a Regional Air pollution INformation and Simulation (RAINS) model that was developed at IIASA.

Total emissions in China are estimated at 9.7 and 11.7 million tons NH_3 in 1990 and 1995 and are forecasted to increase to nearly 20 million tons NH_3 by 2030 in the presented scenario. The major contribution comes from N-fertilizer application and livestock, representing in the 90's about 52 and 41 percent of total emissions, respectively. The share of fertilizer application in total emissions is expected to increase to about 61 percent in 2030, while that of livestock declines to 33 percent. Owing to a large share of ammonium bicarbonate and urea in applied N-fertilizers, the emission structure is in sharp contrast with the situation in Europe where livestock is the dominant source of ammonia and losses from N-fertilizer application represent typically about 15 to 20 percent of total.

Spatial distribution of emissions is also presented at a 1x1 degree grid resolution. In 1995 the highest ammonia emission density which exceeds 100 thousand tons NH_3 per grid, is observed in Jiangsu and Henan provinces. This corresponds well with the large population of pigs in these regions as well as high cattle density in Henan province.

INTRODUCTION

Atmospheric ammonia (NH_3), sulfur dioxide (SO_2) and nitrogen oxides (NO_x) are among the main pollutants leading to acidifying deposition. Since typically, emissions of the latter two are larger and often associated with big stacks and transport sources that are easy to blame for the pollution, NH_3 has received a lot less attention in the past. This has been the case in Europe, North America and also Asia where rapidly growing emissions of SO_2 grabbed the headlines. China is no exception, fast economic growth means increased energy demand that is satisfied by primarily fossil fuels that in consequence might lead to high SO_2 and NO_x emissions and increased acid deposition in China and elsewhere. The issue of acidification in China has been studied in the last years[1,2] and several papers reviewed the present and future emissions of SO_2 and NO_x[1,3,4]. Only few studies on ammonia emissions in China are available[5]. Although there are several global or regional assessments that include China or East Asia[6,7,8], they often lack the necessary level of detail for a regional assessment.

Importance of NH_3 is growing, partly due to continued efforts to reduce emissions of the other acidifying pollutants but also because of its role in eutrophication of ecosystems. Also, similarly to growing energy demand, the output of the agricultural sector is expected to grow in the coming decades[9,10] as well as emissions of NH_3 associated with it.

Recently, several atmospheric modeling studies focusing on acidification have been initiated in East Asia. In order to analyze the present and future acid deposition in that region, spatially disaggregated emission inventories of SO_2, NO_x, and NH_3 need to be compiled. They serve as an input to the atmospheric long-range transport models. This paper focuses on China and provides estimates of NH_3 emissions in 1990 and 1995 as well as projections up to 2030. Emissions are estimated for several sectors on a provincial level using a Regional Air pollution INformation and Simulation (RAINS) model[11] that was developed at IIASA. Spatial distribution of emissions is also presented at a 1x1 degree grid resolution.

METHODS AND DATA

This section presents the methodology used to estimate the emissions of NH_3 in China. The methodology relies on the approach used in Europe[12,13], that is the NH_3 module of the Regional Air Pollution INformation and Simulation (RAINS) model[14], and as far as available, takes into account information about China-specific characteristics.

The standard concept for calculating emissions from a given activity is to multiply an 'activity level' with a representative 'emission factor'. The crucial question in constructing emission inventories relates to the appropriate level of resolution. On the one hand, the disaggregation should be detailed enough to allow capturing the important differences between emission sources. Only in a very few situations do emission sources represent homogeneous populations. In the majority of cases each source has slightly different characteristics. On the other hand, practical considerations, particularly the availability of reliable statistics on activity rates and emission factors, seriously limit the level of detail, which could be meaningfully maintained. Therefore, any emission inventory has to strike a balance between technical detail and practical data availability.

Emissions from Livestock Farming

Ammonia emissions from livestock occur at four stages, i.e., in the animal house, during storage of manure, its application and during grazing periods. These processes are explicitly distinguished in the RAINS database. The NH_3 emissions from livestock (*EL*) are calculated using the following equation:

$$EL_{i,l} = \sum_{j} L_{j,l} \sum_{k} \sum_{s=1}^{4} \left[ef_{i,j,l,s} \left(1 - \eta_{i,k,s}\right) X_{i,j,k,l} \right] \qquad (1)$$

where:

i,j,k,l	= province, animal type, abatement technique, year;
s	= four stages, i.e. animal house, storage, application, grazing;
L	= animal population [thousand heads];
ef	= emission factor [kg NH_3 / animal per year];
η	= reduction efficiency of abatement technique;
X	= implementation rate of the abatement technique.

In order to calculate NH_3 emissions accurately, quantitative data on several parameters[13,15,16] is required. In practice, average emission factors for the four stages mentioned above are derived for each animal type. The minimum information necessary to arrive at region specific emission factors for each animal type includes typical excretion rates, type of the housing and manure storage systems, and the length of the grazing period. Emission factors used in this study are based principally on estimates for developing countries by Bouwman *et al.*[7] but are adjusted for the Chinese specific production efficiency of milk or meat. Additionally, emission rate for dairy cattle is linked to the assumptions about average milk yield (calculated as average per inventory head) in future years. The relation between milk yield and nitrogen excretion, and consequently ammonia emission rate, is derived from Klaassen[16], ECETOC[17] and own assumptions. For other animal categories the changes of production efficiency are taken into account in the forecast of animal numbers but it is assumed that the impact on the emission rates will be of less importance, also there is substantially less information that would enable to derive the appropriate relation. A comparison of NH_3 emission coefficients for different animal categories used in this and other studies is presented in TABLE 1.

Emissions from Mineral Fertilizer Application

Emissions of NH_3 from mineral fertilizer depend on many factors[7,15] including, type of fertilizer applied, soil properties, meteorological conditions, time of application in relation to a crop canopy, and method of application. The nitrogen loss from fertilizer application is region specific but it must be stressed that the uncertainty of emission factors is large. In this work, one important parameter, other than fertilizer type, influencing NH_3 emissions was considered, i.e., temperature, by distinguishing between tropical and temperate conditions (see TABLE 2). However, since there is little experimental data available this was taken into account only for urea and ammonium bicarbonate (the most important fertilizers in China).

Typically, N losses from synthetic fertilizers vary between one and four percent, with the exception of ammonium sulfate (eight percent), urea (15 to 25 percent) and ammonium bicarbonate (ABC) (20 to 30 percent). In China, a large proportion of total N-fertilizer use is represented by urea and ABC; estimated at about 50 and 40 percent, respectively[19,20]. Due to the limited availability of information on the spatial distribution of use of various fertilizers, the RAINS model distinguishes two categories, namely urea and ABC and other nitrogen fertilizers. Weighted average emission factors, based on literature data (TABLE 2) and available statistics on fertilizer consumption[19,20, 21] are derived for all provinces also taking into account differences in losses in temperate and tropical zones. Division of the emission domain into tropical and temperate zones in China is derived from Zhang and Lin[22]. Chinese regions included in the tropical zone (higher N-loss from urea and ABC application) are: Fujian, Guangdong, Hainan, Guangxi, Guagzhou, Guiyan, Guizhou, Hebei, Anhui, Henan, Hubei, Hunan, Jiangsu, Jiangxi, Shanghai, Wuhan, Yunnan, Zhejiang and Hong-Kong. Emissions of ammonia from fertilizer use (*EFC*) are estimated using the following equation:

$$EFC_{i,l} = \sum_{j} (nf_{i,j} \frac{17}{14} * FC_{i,j,l}) \qquad (2)$$

where:

- i,j = province, fertilizer type;
- nf_i = nitrogen loss per fertilizer [% of N content /100];
- FC = fertilizer consumption [Gg N / year];

Since the nitrogen loss is expressed as a percent of the total nitrogen in the fertilizer, the conversion factor (17/14) is used to calculate ammonia emissions.

Emissions from Fertilizer Production

The production of ammonia, urea, nitric acid and fertilizer is the main source of industrial NH_3 emissions. It is assumed that the total production of ammonia plants in each country is proportional to fertilizer production[16]. Emission factors for fertilizer plants vary depending on the profile of the plant, its age and the type of the process. Ranges of emission factors, summarized in the ECOTEC study[17], for various fertilizers manufactured in Western Europe are presented next to the data input by the countries in the CORINAIR database (CORINAIR is a European emission inventory system) (TABLE 3). The emission coefficients for industry should be in fact province specific, however, the information on what fertilizers are produced and where was not found and therefore an average emission factor of 2 kg NH_3/Mg N-fertilizer produced was assumed for the whole of China. Data on total production of fertilizers originates from FAO[20] and national statistics[21].

The provincial data on nitric acid production was not found. As the total emissions from this source are believed to be small they are not included at this stage in the model. Based on available data and quoted emission rate the ammonia emissions in 1990 and 1995 would be about 16 and 28 Gg NH_3 for China.

Other sources of ammonia emissions

Livestock breeding and nitrogen fertilizer application are the largest sources of ammonia emissions but there are several other activities/processes that may contribute a significant portion in some areas. In this section a short discussion of these sources is presented.

<u>Biomass burning</u>

This category includes burning during forest clearing, savanna burning, agricultural waste burning and combustion of biofules for energy purposes. There is evidence that significant amounts of ammonia are released during biomass burning. Bouwman *et al.*[7] reviewed several global estimates of NH_3 emissions from this source, they vary between 2.5 and 7 Tg NH_3. This is approximately 10 to 20 percent of global emissions from animals. In this study this source is not included, however, it is planned to make use of the available land use data as well as recent improvements in biofuel use statistics to estimate regional emissions from biomass burning in the area under study in the near future.

<u>Natural ecosystems, crops and oceans</u>

This source has not been included in NH_3 estimates in this study but the sources of data on land use (providing sufficient spatial resolution) have been identified. Global NH_3 emissions from natural ecosystems and oceans are estimated[7] at about 12 to 28 Tg, of which six to 12 Tg are from natural ecosystems, i.e., soils under natural vegetation, crops and natural vegetation (canopy). All estimates are associated with large uncertainty and there is not enough experimental evidence to distinguish specific emission rates for various types of vegetation, climatic zones, etc. Often, single emission factors are used for all types of crops.

<u>Humans</u>

As a result of normal metabolic processes NH_3 is released from humans (breath, sweat, excretion). There is, however, great variation in estimates of emissions from this source, i.e., 0.01 to 1.3 kg N/person per year. Other sources associated with humans are sewage treatment plants and pets. These sources seem to be either insignificant or very little work has been done on estimating emission rates and therefore there are large uncertainties associated with these estimates. In this study an emission factor of 0.5 kg N per person per year has been assumed after Bouwman *et al* [7]. This emission factor includes emissions from pets.

<u>Fossil fuel combustion</u>

Although there is large uncertainty associated with emission factors from fuel combustion, it is generally believed that they are very small. Some studies report emission factors for this category, mainly for combustion of solid fuels and traffic[15]. It is known that ammonia emissions from cars equipped with three-way catalytic converters are higher than from cars with no emission controls, but there is no agreement on how important they are. Previous studies[15] reported values of around 5 g NH_3/GJ while some more recent measurements[23,24] indicate 15 to 30 g NH_3/GJ. Applying these higher emission rates to the current energy forecast in the RAINS-Asia[14] model and assuming that by 2030 all the cars in China will be equipped with three-way catalyst, the NH_3 emissions from cars would be between 80 and 160 Gg NH_3 (less than 1 percent of agricultural sources). Since cars with no emission control emit even lower quantities of NH_3, their contribution to Chinese emissions in the 1990's is negligible. However, the final estimates presented in this paper do not include traffic due to their large uncertainty and presumably little importance.

Options for Controlling NH_3 Emissions

There exist a large variety of options to control emissions of NH_3 at various stages. For the purposes of this study it is important to identify a limited list of abatement options (groups of techniques with similar technical and economic characteristic) and extrapolate current European operating experience to China. Since information about the important province-specific parameters influencing the applicability of options is not available, only one illustrative abatement scenario is shown in this paper (see further sections). A brief characteristic of major abatement options used in the model is provided below, for more details see UNECE[25].

- Low nitrogen feed, i.e., reduction of nitrogen intake in feed, by more precise matching of dietary supply with animal requirement, resulting in reduced nitrogen output in waste.
- Biofiltration (air purification), i.e., treatment of ventilated air using a biological scrubber that converts the ammonia into nitrate or biological beds where organic matter absorbs ammonia.

- Animal housing adaptation, i.e., improved design and construction of the floor, flushing the floor and climate control, and wet and dry manure systems for poultry.
- Covering storage of manure outdoors, i.e., low efficiency options including the following coverings: floating foils, polystyrene (non-rigid lids) and high efficiency options including the following coverings: tension cap, concrete, corrugated iron, polyester (rigid lids).
- Low ammonia application techniques, distinguishing high efficiency options (immediate incorporation of solid and liquid waste, deep and shallow injection of slurry) and medium to low efficiency techniques (slit injection, trailing shoe, slurry dilution, band spreading, incorporation within 24-hours).
- Substitution of urea/ABC by ammonium nitrate or other 'low N-loss' fertilizer, and
- End-of-pipe options to remove ammonia from waste gases from fertilizer production.

The Database on Agricultural Activities

The estimates of current and future levels of NH_3 emissions in China are based on available statistical information on livestock numbers and fertilizer production and use. For livestock, emission sources are presently aggregated into the categories listed in TABLE 1. Fertilizer industry is represented by three sub-sectors distinguishing between application of urea/ABC and other synthetic N-fertilizers and N-fertilizer production. Other anthropogenic sources are included in one category where emissions from humans and pets are estimated.

<u>Data Sources</u>

The recently created activity database for China in the NH_3 module in RAINS includes data for 1990, 1995, 2000, 2010 and 2030. Statistical data for 1990 and 1995 was collected from a variety of national[21] and international sources[19,20, 26] and the database of the Land Use and Land Cover Change Project (LUC) at IIASA. Chinese statistical yearbooks include also some data for Hong-Kong. To fill-in the gaps, statistical information available via Internet from local offices was retrieved[27]. Both national statistics and the LUC database provide information on province level. The LUC database also includes some information for 1989 to 1993 at the higher spatial resolution. The RAINS-regions correspond to the administrative structure in China. The biggest problems were identified in spatial disaggregation of activity data; often not enough information is available to reflect regional differences and this is where important improvements to the database can be made. For example, the spatial distribution of poultry was not available from published sources and surrogate statistics on regional poultry meat and eggs production were used to arrive at poultry numbers in the provinces. Although data on nitrogen fertilizer use in the provinces was available, the share of urea, ABC and other fertilizers was available on the national level only[19,20]. Due to lack of other information the same distribution was assumed on the provincial level. Data for 2000 are extrapolated from recent statistical information available for 1998 or even 1999 and short term forecast, e.g. FAO[20]; OECD[28].

<u>Forecast of Activity Levels</u>

The principal elements of the forecast developed in this study include assumption on:

- the future per capita consumption of milk, beef, pork, poultry, other meat and rates of fertilizer application,
- the change in efficiency of production or application,
- the import-export balance of dairy products, meat in the future,
- possible impact of the change of efficiency of production on emission rates.

The assumptions listed above were derived on the basis of the analysis of historical data and from agro-economic studies dealing with the agricultural long-term development in East-Asia. In particular, the analysis relies on a comprehensive study carried out by the UN Food and Agriculture Organization[9], on a study performed by OECD[26,28], on the projections of agricultural development in developing countries[6], and on a study looking at China's food economy and its global implications[29] as well as on paper by Simpson[30] on feed requirements and availability in China. From these studies, growth rates characteristic for individual animal types and regions were derived and applied to the latest available livestock data (for 1990, 1995 or 1998). The principal assumptions are that China will increase its production and consumption of meat, milk and grain[9] and the growth will be faster between 1990 and 2010 than between 2010 and 2030. The forecast of fertilizer use and production is based additionally on the analysis of country specific fertilization practices and expansion plans for construction of new fertilizer plant capacity[10,31,32,33,34,35].

It is important to stress that the livestock forecasts take into account foreseen improvements in efficiency of agricultural production in the coming decades[30,36,37]. This includes increase of average milk yields and meat production per inventory head. Many provinces in China were characterized by a very low productivity in the 90's. This is changing, rapid growth in production efficiency (especially meat production) has been observed in the last decade[20,30]. Also the consumption of dairy products and meat continues to grow, although at a slower paste than forecast by the government in mid 80's [37]. These forecasts have been revised by local decision makers and the currently presented views seem to be a lot more realistic which finds also confirmation in statistical data published recently[20,28]. The developed projections of agricultural activities in China that are further used for calculation of NH_3 emissions are summarized in TABLE 4.

Spatial Distribution of Activities

In 30 years from now the agricultural sector might look quite different. The effort was made to include some of the foreseen changes in the forecasts presented in this paper, e.g. increased consumption of agricultural products, some changes in consumption patters, improvement in efficiency of production. The changes in spatial allocation of production, however, could not have been fully incorporated. Often information required to perform such analysis is missing or is very scarce. The spatial distribution of livestock production and production of fertilizers as well land use patterns will be different in the future than the ones we experience now. The information on future developments in the production of fertilizers in China have been included in scenarios presented. The plans of construction of new plants in certain regions (e.g., Hainan, Xinjiang, Nei-Mongol, Shanxi, Shandong, Henan) are discussed in Li[10], Isherwood[31], Wang[34]. The regional differences in growth of livestock production, discussed to some extend in Verburg and Keulen[36] and Chu[38], are not taken into account and equal growth rates are applied to all regions (related to the latest available statistical data).

Spatial Distribution of Emissions

Long-range transport models used to analyze the deposition patterns of acidifying species need as input spatially distributed emission inventories and projections. In principle, gridded emission data should be individually calculated for each grid. In practice, however, none of the data necessary for performing this calculation is available within a spatial grid resolution, so that direct calculation is impossible. Alternatively, the emission volumes were determined at the administrative unit (province) level and further distributed to a regular grid system, i.e., 1x1 degree.

A key question is the identification of appropriate sector-specific surrogate indicators that could be used to allocate the provincial emissions from a given activity into several grid cells. In this work, three such indicators were developed and used, namely the densities of population, large animals and pigs. The gridded population density map was derived from the statistical data for Chinese counties, provinces and cities (above 100,000 inhabitants). For animal density, the county level statistics on the number of pigs and large animals (including cattle, horses, camels, mules, asses, sheep and goats) were used. The animal data is for the period 1989-1993 originates from the database of the Land Use and Land Cover Change project (LUC) at IIASA. No county level data for application of fertilizers was found and at this stage the spatial distribution (within the province) of emissions from this activity is based on the density of livestock (sum of pigs and large animals). Further work is needed to link the application of N-fertilizers with land use databases, this work is in progress.

RESULTS AND DISCUSSION

Estimates of NH_3 emissions in 1990, 1995, 2000 as well as two scenarios for 2030, i.e. BASE and BAT, are presented in TABLE 5 and TABLE 6. Since the BAT scenario is a very preliminary attempt to assess the impact of a 'Western type' emission control options for NH_3, the assessment was performed on the national level only and therefore its results are not included in TABLE 6. Further, the structure of NH_3 emissions in China is compared with the situation in Europe and other East Asian countries (FIGURE 1). Finally, the spatial distribution of emissions in 1995 and 2030 is shown in FIGURE 2 and FIGURE 3.

In the BASE scenario, emissions of ammonia in China increase from 9.7 Tg NH_3 in 1990 and 11.7 Tg NH_3 in 1995 to nearly 20 Tg NH_3 in 2030 (TABLE 5). The largest single source of emissions is the use of urea and ammonium bicarbonate (ABC) which are the key fertilizers in China. Both of these are characterized by high N content but also high N loss after application (see TABLE 2), leading to high ammonia emissions. Application of synthetic N-fertilizers in China is a source of 5, 6 and 12 Tg NH_3 in 1990, 1995 and 2030, respectively, i.e. between 50 and 60 percent of total emissions. This is a very different picture from Europe or other East Asian countries (FIGURE 1). For 1990, in other East Asian countries the share of emissions from N-fertilizers is also relatively high (about 30 percent) when compared to Europe (about 15 percent) but it is substantially less than in China. The share of urea in China is not higher than in some other East Asian countries but China is the only important manufacturer and user of ABC that together with urea takes 90 percent share in total N-fertilizer applied.

The emissions from livestock increase in China from 3.9 Tg NH_3 in 1990 to 4.9 and 6.7 Tg NH_3 in 1995 and 2030. The largest source are pigs representing nearly half of the emissions from livestock in 1990; their share declines by 2030 to 41 percent (14 percent of total NH_3). Share of cattle remains constant over the whole period at the level of about 27 percent while that of poultry is expected to increase from 14 percent in 1990 to 22 percent in 2030 (in absolute terms emissions from poultry increase by a factor of three in the BASE scenario).

In the presented BASE scenario it was assumed that there is no change in practices of applying fertilizers, for example, switching to fertilizers that are more expensive but less prone to NH_3 volatilization. With the forecast annual growth of fertilizer use in China ranging from two to three percent per year and maintaining high share of urea and ABC on the market, synthetic N-fertilizers remain a major source of emissions. Current average N losses from fertilizer application in China are estimated at about 20 percent of nitrogen content. If the production and use of ABC and urea declines, leading to a different mix of fertilizers and consequently lower average N loss, the emissions of NH_3 will also drop. Bouwman and Hoek [6] estimated that reducing the average loss to five percent (currently estimated for the developed countries) would result in declining emissions from fertilizer application in spite of an expected growth in consumption. Assuming a similar transformation in the scenario presented in this study would lead to a decline of NH_3 emissions in 2030 by about 9 Tg, reducing total emissions to around 11 Tg NH_3.

To assess the impact of state-of-the-art controls to reduce NH_3 emissions an illustrative BAT scenario was developed. It assumes introduction of low ammonia application techniques for incorporation of cattle, pig and poultry manure, modern housing and modified feeding strategies for dairy cattle, pigs and poultry, end of pipe controls in fertilizer production plants, as well as replacement of urea and ABC fertilizers with substitutes characterized by lower loss of nitrogen after application. It was assumed that not all but up to 90 percent of urea and ABC will be substituted; this is enough to achieve similar average N-loss rates, for total fertilizer applied, as in Europe, US or Japan in the 90's. Due to lack of detailed data to evaluate the China-specific conditions that would restrict the application of several control options listed above, this scenario has to be used with great caution. Preliminary assessment of this strategy suggests that total emissions of NH_3 could be reduced in 2030 by nearly 60 percent compared to the BASE scenario. Most of the reduction is due to the substitution of urea and ABC (85 percent of total reduced) followed by pigs (7 percent), cattle and poultry (4 and 3 percent).

The spatial distribution of ammonia emissions in 1995 is presented in FIGURE 2. The highest emission density (above 100 Gg NH_3 per grid) is observed in the Jiangsu and Henan provinces. This corresponds very well with the large populations of pigs in these regions as well as the high cattle density in the Henan province. FIGURE 3 presents the distribution of emissions expected for the year 2030 in the BASE scenario. As in the 1990's, the Henan and Jingsu provinces remain among the highest emitters having few grids with emissions above 200 Gg NH_3. But the 'high emission density' area is growing, significantly more grids show emissions above 100 Gg NH_3 also in other provinces, i.e. Hebei, Shanxi and Shandong. It is important to bear in mind that up to 60 percent of total NH_3 originates from application of synthetic N-fertilizers in this scenario and that the data on spatial distribution of this activity is very poor. Changing this distribution would affects significantly the shown emission pattern.

There are very few published estimates of NH_3 emissions for China and none of the identified sources provides province specific estimates. Zhao and Wang[39] estimated for 1990 emissions of NH_3 in China at 13.6 Tg. This is substantially more than this work but they used a very high emission factor for combustion of fossil fuels and in result energy use appears to be one of the most important sources contributing nearly 2.7 Tg NH_3. In more recent ammonia inventories significantly lower values of emission factors have been used and this sector represents a very low share of total emissions, e.g. Bouwman *et al.*[7]. However, even subtracting NH_3 emissions from energy use, Zhao and Wang[39] estimate is higher from this work by more than a million tons of ammonia. There are several factors that contribute to that difference, the most important include different emission factors for livestock as well as for fertilizer application. Zhao and Wang[39] used European values from the beginning of 1990's[16,18] which are for some categories higher than used in this study (see also TABLE 1). Bouwman and Hoek[6] do not give an estimate for China but for the whole of East Asia, about 13 Tg NH_3 in 1990. Since China is by far the biggest contributor in the region, it is expected that their estimate is similar to this work. They also provide a forecast of agricultural activities and emissions until 2025. Some of the assumptions on the development of the agricultural system in China used in this paper are similar to Bouwman and Hoek[6] but the emission forecast cannot be compared directly as they assumed a change in practices of fertilizer application and consequently arrived at lower losses from application of N-fertilizers.

CONCLUSIONS

This paper presents regional emissions of ammonia in China for 1990, 1995 as well as two scenarios for 2030. Current structure of NH_3 emissions in China differs from that of Europe but also from other East Asian countries with application of N-fertilizers contributing more than 50 percent of total. This picture might not change in the future if China will not substitute, at least partly, low N-loss fertilizers for urea and ammonium bicarbonate. In this context it is important to stress the necessity to improve the spatial distribution of emissions from fertilizer application, it is recognized that the distribution pattern presented in this paper is only preliminary.

In spite of the assumed improvements in the efficiency of agricultural production in the BASE scenario, the ammonia emissions are expected to double by 2030. This is largely because of higher application rates of synthetic N-fertilizers needed in order to increase crop production efficiency. Since in the BASE scenario the mix of fertilizers used is as in the 1990's, they continue to play a dominant role in total N-losses from Chinese agriculture. It is crucial that the mix changes in the future so that the losses of N decline significantly. This is illustrated in the BAT scenario where such substitution takes place and achieved NH_3 emission reductions represent about 80 percent of the total reduction.

REFERENCES

1. Downing, R.J., Ramankutty, R., Shah, J.J., *RAINS-Asia - An assessment model for acid deposition in Asia;* The World Bank, Washington, D.C., 1997, p 67.
2. Dianwu Zhao and Zhang Xiaoshan "Acid Rain in Southwestern China". In *Proceedings, Third Annual Workshop on Acid Rain and Emissions in Asia, Nov. 18-21, 1991,* Foell, W.K. and C. Green, Ed.; Asian Institute of Technology, Bangkok, 1991.
3. Streets, D.G., Waldhoff, S.T. "Present and future emissions of air pollutants in China: SO_2, NO_x, and CO", *Atmospheric Environment*, 2000, Vol. 34, 363-374.

4. Aardenne van, J.A., Carmichael, G.R., Levey, H., Streets, D.G., Hordijk, L. "Anthropogenic NO_x Emissions in Asia in the period 1990 to 2020", *Atmospheric Environment*, 1999, Vol. 33, 633.
5. Zhao, D. and Wang, A. "Estimation of Anthropogenic Ammonia Emissions in Asia", *Atmospheric Environment*, 1994, Vol. 28, 689-694.
6. Bouwman, A. F. and Van der Hoek, K.W. "Scenarios of Animal Waste Production and Fertilizer Use and Associated Ammonia Emission for the Developing Countries", *Atmospheric Environment*, 1997, Vol. 31, 4095-4102.
7. Bouwman, A., Lee, D., Asman, A., Dentener, F., Van der Hoek, K., Olivier, J."A Global High-resolution Emission Inventory for Ammonia", *Global Biogeochemical Cycles*, 1997, Vol. 11, 561-587.
8. Olivier, J., Bouwman, A., Van der Hoek, K., Berdowski, J., "Global Air Emission Inventories for Anthropogenic Sources of NO_x, NH_3 and N_2O in 1990", *Environmental Pollution*, 1998, 102, S1, 135-148.
9. *World Agriculture: Towards 2010*, Alexandratos, N., Ed.; An FAO Study. FAO/ J. Wiley & Sons, 1995.
10. Li Zhijian "The Chinese Fertilizer Today and Tomorrow, Presented at the 65th IFA Annual Conference, Beijing 19-22 May, 1997. IFA Agro-Economics Committee, Paris, June, 1997.
11. *The RAINS model of acidification, science and strategies in Europe*, Alcamo, J., R. Shaw and L. Hordijk, Eds.; Kluwer Academic Publishers, Dordrecht, The Netherlands, 1990.
12. Klaassen, G. "Options and Costs of Controlling Ammonia Emissions in Europe", *European Review of Agricultural Economics*, 1994, 21, 219-240.
13. Klimont, Z. *Ammonia Emissions, Abatement Technologies and Related Costs for Europe in the RAINS model*, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 2001 (forthcoming), IR-01-xx.
14. http://www.iiasa.ac.at/~rains
15. McInnes, G., Ed.; "Joint EMEP/CORINAIR Atmospheric Emission Inventory Guidebook, First Edition", European Environmental Agency, 1996, Copenhagen, Denmark.
16. Klaassen, G. *Past and Future Emissions of Ammonia in Europe*, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 1991, SR-91-01.
17. *Ammonia Emissions to Air in Western Europe*, European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC), Brussels, Belgium, 1994, Technical Report No. 62.
18. Asman, W. *Ammonia emissions in Europe: updated emission and seasonal emission variation*, National Environmental Research Institute (DMU), Roskilde, Denmark, 1990, DMU Luft-A132.
19. *World Fertilizer Consumption Statistics*, International Fertilizer Industry Association (IFA), Paris, 1998, No 29, A/98/53.
20. *FAO Statistical Database* (http://www.fao.org), United Nations Food and Agriculture Organization (FAO), Rome, 2000.
21. *China Statistical Yearbook 1998*, State Statistical Bureau, China Statistical Publishing House, Beijing, 1998, No. 17.
22. Zhang, J.; Lin, Z. *Climate of China;* John Wiley & Sons, Inc., New York, and Shanghai Scientific and Technical Publishers, Shanghai, 1992.
23. Fraser, M.P. and Cass, G.R. "Detection of Excess Ammonia Emissions from in-Use Vehicles and the Implications for Fine Particle Control", *Environmental Science & Technology*, 1998, Vol.32, No. 8, 1053-1057.
24. Baum, M.M., Kiyomiya, E.S., Kumar, S., Lappas, A.M., Lord, H.C.III. "Multicomponent Remote Sensing of Vehicle Exhaust by Dispersion Absorption Spectroscopy", *Environmental Science & Technology*, 2000, Vol.34, No. 13, 2851-2858
25. *Control Options/Techniques for Preventing and Abating Emissions of Recuced Nitrogen Compounds*, United Nations Economic Commission for Europe, Geneva, 1999, EB.AIR/WG.5/1999/8.

26. *Agricultural Policies, Markets and Trade in the Central and Eastern European Countries, Selected New Independent States, Mongolia and China; Monitoring and Outlook 1995*, Organisation for Economic Co-operation and Development (OECD), Paris, 1995.
27. Hong Kong Census and Statistics Department; http://www.info.gov.hk/censtatd.
28. *OECD Agricultural Outlook 1999-2004*, Organisation for Economic Co-operation and Development (OECD), Paris, 1999.
29. Lin, J., Huang, J., Rozelle, S. *China's Food Economy: Past Performance and Future Trends. China in the 21st Century. Long-Term Global Implications*, Organisation for Economic Co-operation and Development (OECD), Paris, 1996.
30. Simpson, J.R. "Animal feed requirements and availabilities in China: Projections and policies", *Agricultural Policies in China*, Organisation for Economic Co-operation and Development (OECD), Paris, 1997.
31. Isherwood, K.F. *Fertilizer Demand Situation and Forecasts*, International Fertilizer Industry Association (IFA), Paris, 29 May, 1997.
32. Soh, K.G. and Isherwood, K.F. "A Review of the Current Agricultural and Fertilizer Situation", Presented at the 65th IFA Annual Conference, Beijing 19-22 May, 1997. IFA Agro-Economics Committee, Paris, 1997.
33. Wu So Hai "Fertilizer Production and Market Situation of China", Presented at the 23rd IFA Enlarged Council Meeting, 18-21 November 1997, Monte-Carlo, 1997.
34. Wang, J. "Hainan Island - A Future Fertilizer Production Center", Presented at the 65th IFA Annual Conference, Beijing 19-22 May, 1997, IFA Agro-Economics Committee, Paris, 1997.
35. IFA Secretariat "Global Fertilizer Consumption Trends", Presented at the IFA Agro-Economics Committee Conference, 23-25 June 1997, Centre International de Congrès Tours, France, 1997.
36. Verburg, P.H., van Heulen, H. "Exploring changes in the spatial distribution of livestock in China", *Agricultural Systems*, 1999, 62, 51-67.
37. Vermeer, E.B. "Milk production in China's Municipalities and the role of prices and subsidies", *From peasant to entrepreneur: Growth and change in rural China*; Papers originating from the second European conference on agricultural and rural development in China, Leiden, January 14-17, 1991, Wageningen, Netherlands: Pudoc: distributed by UNIPUB, Lanham, MD., 1992, pp 141-56.
38. Chu, A.C.P. "Sustainable Agriculture: Integrating Pastoral and Arable Land in Southern China; A Model to Increase Arable Land; What Can the New Zealand Experience Contribute?", *Agricultural Policies in China*, Organisation for Economic Co-operation and Development (OECD), 1997, Paris.
39. Zhao, D. and Wang, A. "Estimation of Anthropogenic Ammonia Emissions in Asia", *Atmospheric Environment*, 1994, Vol. 28, 689-694.

KEYWORDS

Emission inventory, Ammonia, China, Spatial distribution, Emission scenarios

ACKONWLEDGEMENTS

This work was partly funded by the Central Research Institute of Electric Institute of Electric Power Industry (CRIEPI), Tokyo, Japan.

Thanks to Sylvia Prieler of LUC project and Wolfgang Schöpp of TAP project at IIASA for their help in preparing the gridded population and animal density maps.

Table 1. Comparison of emission coefficients for livestock [kg NH_3 per animal per year]

Animal category	IIASA[14], Rains-Europe	EEA[15]	Asman[18]	Bouwman *et.al.*[7]	This study
Dairy cows	22.3 - 39.7	28.5	25.1	17.4	19.4 - 24.8
Other cattle	9.7 - 17.7	14.3	25.1	10.0	9.5 - 9.9
Pigs	2.3 - 6.7	4.8	4.8	4.8	4.8
Laying hens	0.16 - 0.42	0.37	0.32	0.24	0.32
Broilers	0.14 - 0.23	0.28	0.32	0.24	0.18
Sheep*	1.1 - 3.0	1.34	1.9	1.2	1.2
Horses**	12.5	8	12.5	10.6	10.6
Camels	-	-	-	12.9	12.9

* - includes goats

** - includes mules and asses

Table 2. NH_3 loss from synthetic N-fertilizers [percentage of N content]

Fertilizer type	EEA[15]	ECETOC[17]	Asman[18]	Bouwman *et.al.*[7]	This study
Ammonium sulfate	8	5 - 15	8	8	8
Ammonium nitrate	2	1 - 3	2	2	2
Anhydrous ammonia	4	4	1	4	4
Urea	15	15 - 20	15	15/25*	15/20*
Combined ammonium phosphates	2-5	5	4	2-5	3
Ammonium bicarbonate (China)	-	-	-	20/30*	20/30*
Other complex NK, NPK fertilizers	2	1 - 5	2.5 - 4	2 - 4	2 - 4
Nitrogen solutions	8	8	-	2.5	2.5

* - Loss assumed for temperate and tropical zones, respectively

Table 3. Default emission factors for different types of fertilizer plants [kg NH_3/Mg N]

	ECOTEC[17]		CORINAIR'1990
Product	Weighted average	Range	Range
Ammonia	0.006	-	0.6 - 1.3
Ammonium nitrate	0.298	0.01 - 0.49	0.25 - 1.75
Calcium ammonium nitrate	1.370	0.16 - 2.96	-
NPK fertilizers	3.083	0.01 - 9.33	0.2 - 12.5
Nitric acid	0.046	0.02 - 0.23	0.01
Urea	5.075	0.69 - 9.33	0.5 - 5.3

Table 4. Activity data used in ammonia calculations for China:
livestock numbers [1000 head]; nitrogen fertilizer consumption and production [Gg N]

Category	1990	1995	2030
Cattle	102,886	132,063	160,790
Pigs	362,712	441,800	571,745
Sheep and goats	210,021	276,856	461,644
Poultry	2,452,229	3,858,254	6,765,601
Horses, asses, mules	26,867	25,849	19,346
Camels	463	351	232
N-fertilizers consumption	19,450	23,383	47,218
N-fertilizers production	14,636	18,594	45,031

Table 5. Emissions of ammonia by category in individual countries [Gg NH_3]

Category	1990	1995	2030-BASE	2030-BAT
Cattle	1039.6	1340.6	1715.9	1300
Pigs	1744.1	2124.4	2749.3	1900
Sheep and goats	249.9	329.5	549.4	500
Poultry	536.1	843.4	1479.0	1100
Horses, asses, mules	283.8	273.1	204.4	204
Camels	6.0	4.5	3.0	3
N-fertilizers consumption	5073.4	6049.0	12173.7	2300
N-fertilizers production	29.3	37.2	90.1	45
Other	696.0	736.0	901.0	901
Total	**9658**	**11738**	**19866**	**8253**
of which:				
Livestock	*3860*	*4916*	*6701*	*5007*
Other sources	*5799*	*6822*	*13165*	*3246*

Figure 1. Comparison of NH_3 emission structure in China, Europe and East Asia, data for 1990.

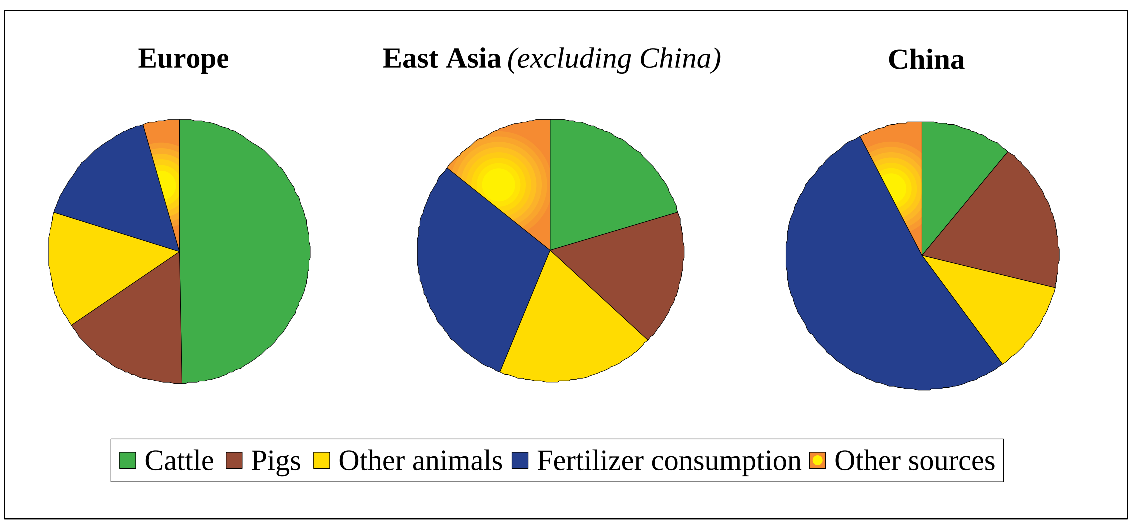

Table 6. Ammonia emissions in Chinese provinces [Gg NH_3]

Province name	Year 1990	1995	2030
Beijing	51	62	68
Fujian	245	284	504
Guangdong	597	638	1111
Hainan	61	70	116
Guangxi	369	456	731
Guizhou	251	306	477
Hebei	528	737	1295
Anhui	501	587	1031
Henan	776	995	1740
Hong-Kong	6	5	7
Hubei	513	673	1208
Hunan	506	608	1042
Inner Mongolia	201	246	423
Ningxia	38	47	81
Jiangsu	741	862	1601
Jiangxi	309	388	657
Heilongjiang	198	293	498
Jilin	218	278	473
Liaoning	274	338	559
Shanghai	100	115	87
Shaanxi	213	262	449
Gansu	168	189	280
Shandong	695	973	1656
Shanxi	157	188	309
Sichuan	864	947	1487
Tianjin	27	37	41
Tibet	80	85	112
Qinghai	95	92	115
Xinjiang Uygur	165	203	409
Yunnan	357	424	664
Zhejiang	354	349	632
CHINA	9658	11738	19866

Figure 2. Spatial distribution of NH_3 emissions in China in 1995 [Gg NH_3/grid]

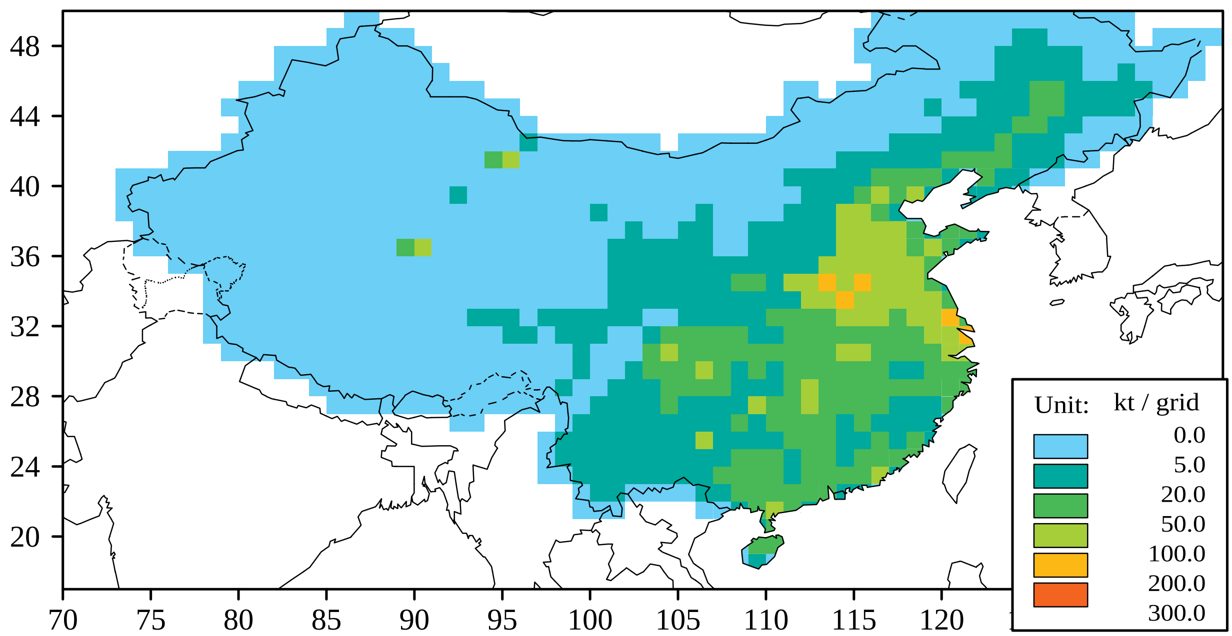

Figure 3. Spatial distribution of NH_3 emissions in China in 2030 (BASE scenario) [Gg NH_3/grid]