Atmospheric Environment 103 (2015) 215–221

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Evolution of farm and manure management and their influence on ammonia emissions from agriculture in Switzerland between 1990 and 2010

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HIGHLIGHTS

- We modeled agricultural ammonia emissions in Switzerland between 1990 and 2010.
- Representative model inputs were produced by surveys on farm and manure management.
- Agricultural ammonia emissions decreased by 16% between 1990 and 2010.
- Severe changes in farm and manure management strongly influenced ammonia emissions.
- Operations counteracting emission mitigation may pose a challenge to regulators.

ARTICLE INFO

Article history:
Received 25 July 2014
Received in revised form
4 November 2014
Accepted 9 December 2014
Available online 11 December 2014

Keywords:
Livestock
Emission modeling
Ammonia
Sensitivity analysis

ABSTRACT

The evolution of farm and manure management and their influence on ammonia (NH_3) emissions from agriculture in Switzerland between 1990 and 2010 was modeled. In 2010, total agricultural NH_3 emissions were 48,290 t N. Livestock contributed 90% (43,480 t N), with the remaining 10% (4760 t N) coming from arable and fodder crops. The emission stages of grazing, housing/exercise yard, manure storage and application produced 3%, 34%, 17% and 46%, respectively, of livestock emissions. Cattle, pigs, poultry, small ruminants, horses and other equids accounted for 78%, 15%, 3%, 2% and 2%, respectively, of the emissions from livestock and manure management. Compared to 1990, total NH_3 emissions from agriculture and from livestock decreased by 16% and 14%, respectively. This was mainly due to declining livestock numbers, since the emissions per animal became bigger for most livestock categories between 1990 and 2010. The production volume for milk and meat remained constant or increased slightly. Other factors contributing to the emission mitigation were increased grazing for cattle, the growing importance of low-emission slurry application techniques and a significant reduction in the use of mineral fertilizer. However, production parameters enhancing emissions such as animal-friendly housing systems providing more surface area per animal and total volume of slurry stores increased during this time period. That such developments may counteract emission mitigation illustrates the challenge for regulators to balance the various aims in the striving toward sustainable livestock production. A sensitivity analysis identified parameters related to the excretion of total ammoniacal nitrogen from dairy cows and slurry application as being the most sensitive technical parameters influencing emissions. Further improvements to emission models should therefore focus on these parameters.

1. Introduction

In 1999, ammonia (NH_3) was included as an air pollutant in the Gothenburg Protocol. The protocol aims at reducing acidification, eutrophication and ground-level ozone, within the framework of the Convention on Long-range Transboundary Air Pollution (UN/

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http://dx.doi.org/10.1016/j.atmosenv.2014.12.024

ECE, 1999). Member countries of the convention have to report regularly on the amount of NH_3 emitted and to achieve national emission ceiling values. The target for Switzerland was a reduction of 13% in the period 1990–2010.

NH_3 emission calculations for Switzerland were compiled and published by Stadelmann et al. (1998) for 1990 and 1995 and by Reidy et al. (2008a) for 1990, 1995, 2000 and 2003. In all years considered, agriculture contributed about 93–95% to the total national NH_3 emissions. This is in line with other publications showing that agriculture is the major contributor of ammonia emissions to the atmosphere (Velthof et al., 2012).

For this paper, the evolution of farm and manure management was investigated and the development of ammonia emissions between 1990 and 2010 was modeled. The relationship between the evolution of emission levels and the changes in farm and manure management were evaluated. Additionally, a sensitivity analysis was conducted in order to determine the most important model parameters influencing emissions and thereby to identify the parameters requiring improvement in order to obtain more accurate emission data.

2. Materials and methods

2.1. Emission model

The NH_3 emission calculations for Swiss agriculture were performed using the Agrammon model which we developed for farm-specific and regional emission calculations (Kupper et al., 2010b). Similar to other models used for recent national inventories (Reidy et al., 2008b, 2009), Agrammon is a comprehensive N-flux model (Bonjour et al., 2014).

2.2. Mail survey on farm and manure management

In order to generate the input data for the model, a detailed representative investigation on farm and manure management was conducted in Switzerland by means of a mail survey in 2010 and 2007. For these years, a stratified random sample of 6351 and 6565 farms, respectively, was used, representing 11% of Swiss farms, both in 2010 and 2007. For 2002, the survey carried out by Reidy et al. (2008a), which included 3877 farms (7%), was adopted. These farms met either of the following criteria regarding the minimum farm size:

a) Surface area: utilized agricultural area (UAA) higher than 10 ha, or for farms growing vegetables, fruit or vines on more than 10% of the UAA: more than 1 ha.
b) Livestock number: more than 6 dairy cows, 40 other types of cattle, 20 horses, 50 sheep or goats, 25 sows, 200 other types of pigs present on the farm.

For each of the surveys, about 10,000 farms which did not meet these criteria were excluded from the survey, representing c. 3% of livestock numbers expressed as livestock units.

Farm classes were defined for the stratification accounting for three altitude zones (valley, hill, mountain), three geographical regions and five farm types (arable farms, cattle farms, pig or poultry farms, mixed farms, other farms). The minimum number of datasets required for each farm class was set at 20. Assuming an average return rate of completed questionnaires of 40%, a minimum sample size of 50 farms per farm class was determined.

The selected farms received a 12-page questionnaire containing approximately 300 questions on major farm and manure management parameters regarding (i) livestock rations, i.e. types of roughage and amount of concentrates in summer and winter dairy cow rations and the protein content of pig rations, (ii) housing systems, (iii) types of manure stores and (iv) techniques used for application of slurry and solid manure. The questionnaire was designed to allow straightforward completion by farmers within about half an hour and automated data registration of completed questionnaires. Data from the survey was combined with existing, routinely collected statistical data (Section 2.4). Before the start of the survey, an information campaign on the project was launched in farming magazines. The 2010 survey had a return rate of 47%, which yielded 2957 datasets, and that of 2007 48% with 3133 datasets (2002: return rate: 50%, 1950 datasets).

Since surveys comparable to the recent ones are not available for the period before 2002, the data on farm and manure management for 1990 and 1995 were determined using the reviewed expert assumptions from Menzi et al. (1997), information from literature (Meyre et al., 2000; Saxer et al., 2004) and recent expert judgment. The latter was crosschecked and adapted where necessary based on the trends obtained for the period between 2002 and 2007. An overview of the data on livestock and manure management fed into the model is provided in the Supplementary information, Table 1.

2.3. Control and transformation of the data

All data from the 2010, 2007 and 2002 surveys were anonymized and transferred to a database which was used for further analyses. Tests were performed regarding plausibility for missing and ambiguous entries in the questionnaire. Missing or ambiguous entries were replaced by values for the most common or most plausible production techniques relating to the respective farm class. Ambiguous values for parameters with a significant influence on emissions (e.g. coverage of slurry stores, manure spreading techniques) were replaced by values that would result in highest emissions in order to avoid an underestimation of the emissions. A detailed description is given in Kupper et al. (2010a). A concerted evaluation of the returned questionnaires with respect to missing or ambiguous entries was carried out for the 2007 and 2010 surveys. The total average proportion of missing, ambiguous and erroneous entries was approximately 10% of all entries per questionnaire. It can be concluded that the related corrections only moderately influenced the resulting data on farm and manure management.

2.4. Statistical data

The statistical information on animal numbers and farming surface area was obtained from the official census conducted on a

Table 1
Animal numbers for the principal livestock categories (numbers for 1990, 1995, 2002 2007 and 2010) and the differences (Δ) between 1990 and 2010 in percentage of the numbers for 1990.

Animal category[a]	1990	1995	2002	2007	2010	Δ 1990 −2010
Cattle in total	1,855,200	1,748,274	1,593,697	1,571,764	1,591,233	−14%
Dairy cows	783,100	739,641	657,924	614,795	589,024	−25%
Other cattle	1,072,100	1,008,633	935,773	956,969	1,002,209	−7%
Pigs in total	1,499,083	1,191,676	1,245,338	1,256,370	1,282,320	−14%
Breeding pigs	474,457	423,769	477,451	489,480	494,171	4%
Fattening pigs	1,024,627	767,906	767,887	766,890	788,149	−23%
Poultry in total	5,938,229	6,250,664	7,338,616	8,228,464	9,024,903	52%
Equids in total	34,041	48,925	64,445	74,881	82,520	142%
Small ruminants in total	239,665	229,011	270,039	292,075	295,279	23%

[a] Detailed numbers on the 24 livestock categories are given in the (Supplementary information, Table 2).

yearly basis by the Swiss Federal Statistical Office (FSO, Table 1). Data on the surface area of alpine pastures was taken from the official soil use statistics (FSO, 2013). Figures on the use of mineral fertilizer N were obtained from the statistics provided by Agricura (2011), which were available for the entire time period 1990–2010.

2.5. Emission calculations

NH_3 emission calculations for 2010, 2007 and 2002 were individually performed for each farm included in the analysis using the Agrammon single farm model (Kupper et al., 2010b). The model simulates the mass flow of total ammoniacal nitrogen (TAN) from excretion through the stages of the manure handling chain (grazing, housing/exercise yard, manure storage and application) at farm level for 24 livestock categories. For each of the 32 farm classes of the survey (altitude x region x farm type) and for each livestock category, a weighted average emission factor (EF) per animal per year for each stage was calculated. Up-scaling of the emissions to the national level was achieved by multiplying these EFs with animal numbers of the respective classes. The results were combined by emissions from mineral and recycling fertilizer application as well as the ammonia exchange between agricultural crop- and grassland and the atmosphere. The latter was calculated using corresponding EFs (Schjoerring and Mattsson, 2001) and the agricultural surface area. A compilation of the EFs used in the model is provided in Kupper and Menzi (2014).

2.6. Time trend

Emissions for the years 2010, 2007 and 2002 were calculated using the EFs derived in this study. For 1990 and 1995, a simplified calculation at the national scale with the Agrammon regional model was performed because no representative data from individual farms was available. The Agrammon regional model employs the same algorithms as the Agrammon single-farm model but calculates emissions at a regional level using input on the proportion of different options and techniques regarding farm and manure management. Total animal numbers and farming surface area at the national scale were used instead of individual farm data.

Emissions for the periods between the years with calculated emissions were determined by interpolation of the EFs times the livestock numbers of the respective year. The difference in the applied methodology for the years 1990/1995 and 2002/2007/2010 suggests that the emission time series might lack consistency to some extent.

2.7. Sensitivity analysis

In order to determine the most important technical parameters of the emission model, a sensitivity analysis was carried out using Monte Carlo (MC) simulations on the Agrammon regional model. Input data included the statistical data for 2007 as described in Section 2.4 and the average values of the farm and manure management data derived from the mail survey (see Section 2.1). For the 336 technical parameters of the Agrammon model, the sensitivity analysis was done with an uncertainty level of ±10% and ±20%. This approach was chosen since the uncertainty is mainly influenced by the technical parameters with high sensitivity and due to a lack of basic data to reliably estimate the individual uncertainly for each of the parameters. In several cases, it was not possible to apply an uncertainty of ±10% and ±20% as the parameter was limited on one side. This irregularity is one reason for the results of the MC simulations not being normally distributed. The MC simulations were performed with 5000 runs per simulation, a number which was sufficient to generate stable output values. Since the Shapiro–Wilk tests for normal distribution of the MC simulation results were mostly negative, standard deviations were not given. However, the average value and the range containing 95% of the output values are provided to indicate the range of the emission calculation. Additionally, the MC simulation results were computed as linear regression, which gives the fraction of the variance in the response variable. This is explained by the linear regression and is characterized by the coefficient of determination (R^2). Technical parameters yielding an $R^2 > 0.005$ are considered to be important and are discussed further.

3. Results

3.1. Evolution of farm and manure management between 1990 and 2010

3.1.1. Housing systems, exercise yards and grazing

The proportion of dairy cows kept in loose housing systems (Pain and Menzi, 2011) was 6% in 1990 and 48% in 2010. For 2010, this number can be subdivided into 47% cubicle housings and 1% deep litter systems. Concurrently, the use of tied housings evolved inversely, falling from 94% in 1990 to 52% in 2010. For the other cattle categories, a similar trend toward loose housing systems occurred even though the increase was less pronounced because loose housings were already more common in these categories in 1990 than for dairy cows. Beef cattle exhibited an almost

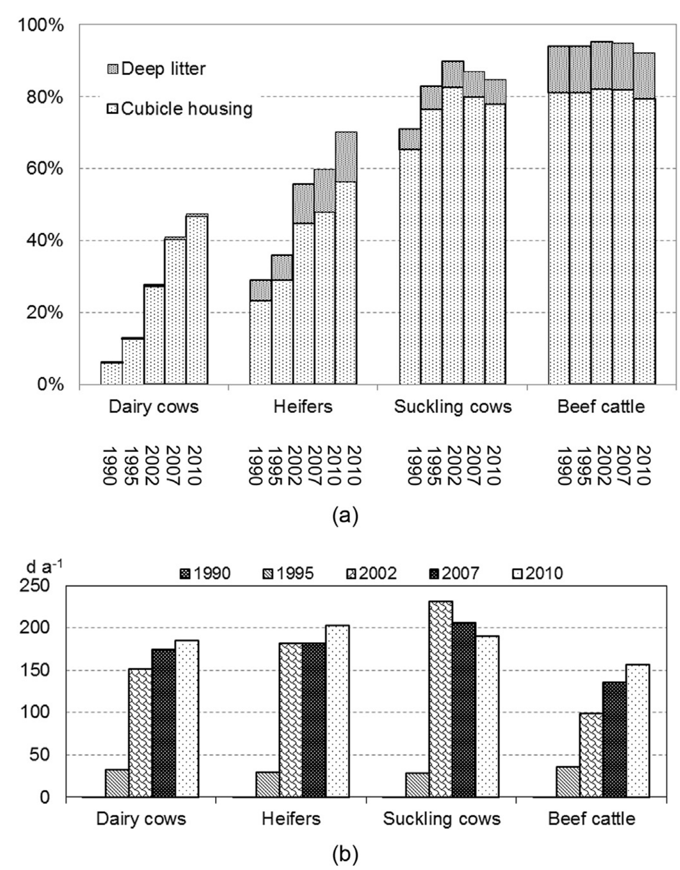

Fig. 1. Evolution of (a) the percentage of loose housing systems (i.e. cubicle housings and deep litter systems) and (b) the duration of access to exercise yards in days per year for dairy cows, heifers, suckling cows and beef cattle between 1990 and 2010.

unchanged level of more than 90% of animals kept in loose housing systems (Fig. 1a). Parallel to the evolution of loose housing systems, exercise yards became common, which is reflected in the increasing average number of days per year that cattle had access to such facilities (Fig. 1b).

The percentage of grazing animals and the duration of grazing also increased, resulting in a higher average grazing time between 1990 and 2010 for all cattle categories (Fig. 2). For dairy cattle, the proportion of grazing animals increased from 67% to 96%, reaching an average of 1595 grazing hours per year by 2010. For heifers and suckling cows, the increase was less pronounced since grazing was already important for these categories in the 1990s. For beef cattle, a strong increase in grazing animals occurred, as for dairy cows, although at a much lower level.

Similar to cattle, a trend toward animal-friendly housing systems was observed for pigs. Animal-friendly means that the animals are kept in groups and have free access to a resting and an exercise area with the latter being mostly located outdoors. Conventional housing with partly or fully slatted one-area pens were widely replaced by multi-area pens with littered areas or combined lying and feeding cubicles connected to outside yards, which reached an occurrence of 84% for dry sows and 60% for fattening pigs by 2010 (data not shown). However, conventional systems with partly slatted floors and without outside yards were still used for 68% of both nursing sows and weaned piglets. For growing hens and laying hens, the use of aviary housing systems with manure belts, often combined with a veranda and/or a free range increased, reaching about 80% occurrence by 2010 (data not shown). This trend paralleled a decline in deep litter and deep pit systems (cage poultry housing was prohibited in 1992).

3.1.2. Storage of slurry and manure application

The total volume of slurry stores was 12.4×10^6 m^3 in 1990 (Saxer et al., 2004) and increased to 16 to 20×10^6 m^3 by 2010. Between 2002 and 2010, the storage volume remained almost unchanged although the share of housing systems producing slurry increased. The percentage of slurry stored uncovered slightly increased from 13% to 17% between 1990 and 2010. While the major part of slurry stores had a solid cover (87% of the volume in 1990 and 67% in 2010), the percentage of perforated covers had increased to 16% of the storage volume by 2010 (0% in 1990). Alternative equipment for reducing emissions from uncovered stores such as tents or floating covers was used for less than 1% of the volume in 2010.

Trailing hoses were not used in 1990. The proportion of slurry applied with this technique increased from 9% in 2002 to 25% in 2010. The use of trailing shoes and slurry injection was negligible.

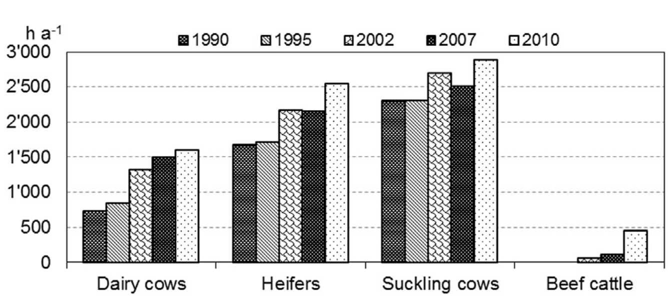

Fig. 2. Evolution of the duration of access to pastures (hours per year) for dairy cows, heifers, suckling cows and beef cattle between 1990 and 2010.

3.2. Emissions

3.2.1. Ammonia emissions in 2010

Total agricultural NH_3 emissions in 2010 were 48,290 t N, representing 92% of total Swiss ammonia emissions. Within agriculture, livestock and manure management contributed 90% (43,480 t N) and the remaining percentage (10%) originated from mineral N fertilizers (2030 t N), recycling fertilizers (360 t N) and crop surfaces/grassland (2370 t N). Cattle, pigs, poultry, small ruminants and horses/other equids accounted for 78%, 15%, 3%, 2% and 2%, respectively, of the emissions from livestock and manure management. Dairy cows and fattening pigs were the prevalent categories, producing 49% and 10%, respectively, of the livestock emissions. The distribution across the emission stages of grazing, housing/exercise yard, manure storage and application was 3%, 34%, 17% and 46%, respectively.

3.2.2. Evolution of ammonia emissions between 1990 and 2010

Between 1990 and 2010, total agricultural NH_3 emissions declined by 16% from 57,280 t N to 48,290 t N and emissions from livestock and manure management by 14% from 50,320 t N to 43,480 t N, respectively (Supplementary information, Table 3). This decline mainly occurred in the 1990s. The lowest level was reached in 2004 (47,010 t N; Fig. 3). Air monitoring data for the period 2000 to 2010 showed almost constant NH_3 concentration levels of NH_3 for 14 monitoring locations and a slight increase in ammonia for two locations (Thoni and Seitler, 2013). It can thus be concluded that the emission pattern calculated since 2000 coincides with the monitoring data. The decrease in ammonia emissions between 1990 and 2010 from cattle and pigs was 12% and 29%, respectively. Poultry, horses/other equids and small ruminants exhibited an increase of 6%, 97% and 21%, respectively.

Emissions from arable and fodder crops (fertilizer and ammonia exchange between agricultural crop- and grassland and the atmosphere) almost continuously decreased between 1990 and 2010 (total reduction by 32%). This coincided with a decline of 20% in the total use of mineral fertilizer N and a decrease from 24% to 13% in the share of urea of total N mineral fertilizer use.

The contribution of cattle to total agricultural emissions remained at an almost unchanged level of about 70% during the period studied. The percentage of ammonia emissions from pigs slightly decreased from 16% to 13% between 1990 and 2010 while the sum of emissions from poultry and other livestock (small ruminants and horses/other equids) increased from 5% to 7% (data not shown).

The total amount of TAN excreted by livestock declined by 13% between 1990 and 2010 (Fig. 4). Emissions from the grazing and

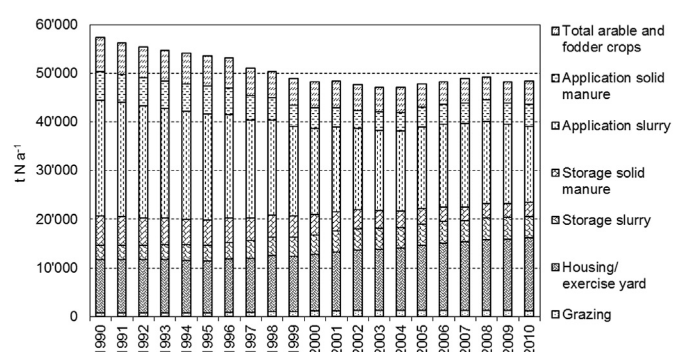

Fig. 3. Evolution of ammonia emissions from agriculture between 1990 and 2010 divided into grazing, housing/exercise yard, manure storage, manure application and arable and fodder crops (t N per year).

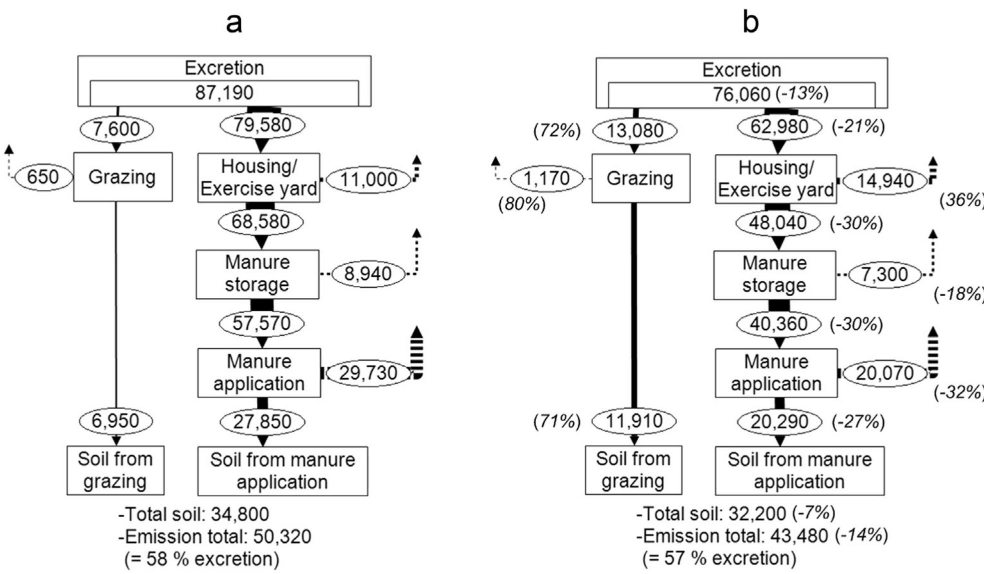

Fig. 4. TAN flows (t TAN) and ammonia emissions (t N) from livestock in Switzerland for (a) 1990 and (b) 2010 including the difference between 1990 and 2010 in percent (between brackets, written in italics). Data on emissions and flows (TAN, N) per animal for each of the 24 livestock categories is provided in the Supplementary information (Tables 5–9).

housing/exercise yard stages increased by 80% and 36%, respectively, between 1990 and 2010. In contrast, a decline of 18% and 32% was observed for emissions from manure storage and application, respectively. This decrease accompanied a reduction in emissions from solid manure (−52% for storage and −25% for application) while emissions from slurry storage increased by 52% but declined by 34% for slurry application. The distribution of emissions from the different emission stages changed strikingly in the time period studied. In 1990, 59% of the emissions from livestock and manure management were due to manure application compared to only 46% in 2010. Inversely, the share of emissions from housing/exercise yard and grazing increased from 22% and 1% in 1990 to 34% and 3% in 2010, respectively.

The percentage of TAN and total N reaching the soil relative to the amount excreted by livestock remained unchanged at a level of 43% and 66%, respectively, from 1990 to 2010 (data not shown for total N).

3.2.3. Sensitivity of the model

The MC simulation yielded an average NH_3 emission from livestock of 48,200 t N and 48,400 t N calculated with an uncertainty level of 10% and 20%, respectively (Supplementary information, Table 4). This complies well with total emissions from agriculture of 48,850 t N according to the inventory for 2007. The ranges of emissions resulting from the 20% uncertainty level are generally higher than from the 10% level. Here, we focus on the 20% level since we consider this value more appropriate for the most sensitive parameters. For total agricultural emissions, the range was between 41,100 t N and 56,700 t N. The deviation from the average ranged from −15% to +17%. The numbers for the emission stages were similar. Manure application exhibited the highest relative deviation (−26% – +29%). The technical parameters showing the highest sensitivity relative to total agricultural emissions are the standard N excretion of dairy cows (i.e. the N excretion before correction due to feeding) with $R^2 = 0.286$ and the share of TAN in excreta of dairy cows with $R^2 = 0.244$. This can be explained by the overwhelming influence of dairy cows, since they contribute nearly half of the TAN excreted by livestock and, indeed, of total emissions. Additionally, emissions at each stage depend on the TAN inflow, which is related to the amount of N and TAN excreted. Two other parameters with a high sensitivity ($R^2 > 0.05$) refer to the EF for slurry application. Their importance is due to the high contribution of slurry application to the total emissions (Fig. 3). A further seven technical parameters exhibited $R^2 > 0.005$ (data not shown). They are mostly factors which influence the amount of TAN excreted by fattening pigs and other cattle categories as well as the emissions from the application of solid manure. All the remaining technical parameters play a minor role with respect to total emissions. Although emissions from housings and exercise yards are the second most important emission source, the sensitivity of this stage is much lower. This might be due to the higher number of parameters influencing emissions from housings/exercise yards such as duration of grazing, housing types, type and occupation of the exercise yard which may counterbalance each other to some extent. The results obtained by the MC simulation are in line with the findings obtained by Sheppard et al. (2007).

4. Discussion

The emission calculations for the period of 1990–2010 yielded two notable outcomes: (i) a slight decrease in total ammonia emissions and (ii) a striking change in the ammonia emissions across the different stages. Both results can largely be explained by two distinct factors: (i) the number of animals and (ii) the shift in production systems, mainly housing systems for cattle and pigs as well as increased grazing and low-emission application techniques for slurry. These issues will be discussed below.

4.1. Number of animals and their performance

The milk yield of dairy cows was 4940 kg y^{-1} in 1990 and increased to 7156 kg y^{-1} by 2010. Total milk production increased only slightly between 1990 and 2010 since it was restricted by quotas until 2009, which were then replaced by contracts between milk producers and the dairy industry. As a consequence, fewer cows were needed to produce the amount of milk required by the market, which is reflected in a 14% decrease in the number of dairy cows between 1990 and 2010. Farms which stopped dairy production often replaced dairy cows by suckling cows. The latter exhibited an increase in number by a factor of c. 8 between 1990 and 2010. However, the total number of dairy and suckling cows was 12% lower in 2010 compared to 1990. As for dairy production, the amount of beef meat produced slightly increased between 1990 and 2010 thanks to progress in animal performance and higher carcass weights (Gerwig, 2008). Similar to dairy cows, pigs exhibited a 14% decrease in animal numbers between 1990 and 2010 (Table 1). This was due to a decrease in pork consumption, increasing pork imports and progress in animal performance (Gerwig, 2008). Overall, the production of pig meat decreased by only 8% during the same time period (Gerwig, 2008; Proviande, 2011).

4.2. Farm and manure management

The clear trend toward housing systems providing a higher surface area per animal and more outdoor exercise (i.e. exercise yards, grazing) was due to statutory regulations aiming at the improvement of animal welfare which were implemented from the mid-1990s onwards. At the same time, the new agricultural policy launched incentive programs promoting regular outdoor exercise for livestock and animal-friendly housing systems (FOAG, 2011). In addition, market-driven label programs promoting such housing systems and regular outdoor exercise for livestock were widely established and supported the development initiated by the new statuary regulations and policy-driven initiatives. For cattle, it was reinforced by the potential for reducing workload due to grazing and loose housing systems, which led farmers away from tied housing when they rebuilt their facilities.

These changes strikingly influenced the distribution of ammonia emissions across the different stages. Due to the strong increase in the grazing of cattle, TAN excretion on grassland and emissions from grazing almost doubled between 1990 and 2010 (Fig. 4). More important was the impact of increased grazing on the TAN flow into the housing/exercise yard stage, which concomitantly decreased by 21%. Since the EF for grazing implemented in the Agrammon model (8.3% of TAN; Kupper and Menzi, 2014) is much lower than the sum of the EFs for housing/exercise yard, storage and application, the potential for ammonia volatilization through the entire production chain was significantly reduced. However, the shift from tied housing to loose housing systems induced a strong increase in the emissions from cattle housings since the latter emit more ammonia (Amon et al., 2001). Additionally, the rapid increase in exercise yards for cattle enlarged the emitting surface in the housing area and thus substantially contributed to higher ammonia emissions (Misselbrook et al., 2006). The ammonia volatilization from pig housings also increased since conventional housings were largely replaced by housing systems with multi-area pens with a littered area and an outside exercise yard. The latter housing type emits roughly twice the emissions compared to conventional housings (Berry et al., 2005).

Thus, the ammonia emissions from housings/exercise yards increased by 36%. This rise in emissions combined with the smaller TAN flow into housing led to a reduction in the TAN flow to manure storage by 30% between 1990 and 2010. Consequently, emissions from manure storage diminished by 18% and the TAN flow reaching manure application decreased by 30% between 1990 and 2010. The lower TAN flow combined with the increasing use of emission-reducing spreading techniques induced a 32% reduction of emissions from manure application. The enhanced use of low-emission application techniques was principally due to recent voluntary programs aiming at reducing gaseous nitrogen losses after application.

Although much less important, the reduction of emissions from arable and fodder crops deserves to be mentioned. This was mainly the consequence of the decreased use of mineral fertilizer N, which was driven by the new direct payments for ecological programs. They were introduced as voluntary programs in 1993 and as a mandatory requirement in 1998 and, among other restrictions, obliged compliance with an equilibrated nutrient balance of N and phosphorus. For most farms, this meant a significant cut in mineral fertilizer use if they wanted to avoid a reduction in their animal stock. Additionally, N included in recycling fertilizers (mainly sewage sludge, compost) diminished by two thirds during the same period (Supplementary information, Table 3). Their application strongly decreased after 2000 because of the announcement of a ban on sewage sludge application for 2006 (Spiess, 2011).

5. Conclusions

The interactions between the main influencing factors, i.e. the number of animals and a shift in production systems, resulted in a 14% reduction of ammonia emissions from livestock between 1990 and 2010. Moreover, the share of the emission stages relative to the total emissions changed. In 1990, 77% of the emissions from livestock and manure management were due to manure storage and application, while it was 63% in 2010. The share of emissions from the housing/exercise yard and grazing stages increased from 22% and 1% of total emissions from livestock and manure management in 1990 to 34% and 3% in 2010, respectively.

The most influential driver for this development was the strong focus on animal welfare leading to a clear increase in animal-friendly housing systems providing a larger surface area per animal and regular outdoor exercise both on exercise yards and during grazing. The trend was most pronounced for the prevailing livestock categories dairy cows, with respect to housing, exercise yards and grazing, and fattening pigs, with respect to housing systems. This development was mainly driven by statutory regulations which aimed at the improvement of animal welfare. Public opinion was an important driver here.

This development illustrates the challenge for regulators to balance different aims in the striving toward sustainable livestock production. There is a need to elucidate to what extent counteracting measures can be avoided. A reduction in emitting surfaces can be achieved without a deterioration in animal welfare by promoting constructional measures for housing and minimizing the use of exercise yards e.g. during the grazing season. Synergistic effects between emission reduction and animal welfare can be achieved if floors are well drained, thus limiting the risk of, for example, claw diseases (Becker et al., 2014). Furthermore, measures that enhance an equilibrated nutrient balance at the farm level, as implemented in Switzerland, act synergistically toward emission mitigation.

N flows and the contribution of different emission stages to total agricultural ammonia emissions can change considerably over a period of 20 years. Reliable and detailed emission monitoring is therefore necessary. It must include a periodic and detailed monitoring of farm and manure management combined with an updated emission model based on N flows. If the precision of the most sensitive technical parameters influencing emissions, as derived from the sensitivity analysis, can be improved, higher accuracy of the calculated emissions can be achieved. Therefore, further improvements should focus on these parameters, which are the amount of N and the share of TAN in excretions from dairy cows as well as the emission factors for slurry application.

Acknowledgments

We are grateful to the farmers participating in the farm management surveys. We thank Mamoun Bencheikh, Daniel

Bohnenblust, Jan Potterat and Arthur Zesiger (Swiss Federal Office for Statistics) for the conception of the farm survey and for supplying activity data. Elizabeth Steele (School of Agricultural, Forest and Food Sciences, Bern University of Applied Sciences) is acknowledged for linguistic revision of the manuscript. The project relied on the financial support of the Federal Office for the Environment FOEN, Air Quality Management Section (grant number 06.9113.PZ / J415-1989).

The mass flow diagrams were produced using the STAN 2.5 software (Institute for Water Quality, Resource and Waste Management, Vienna University of Technology).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2014.12.024.

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