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Are Adaptation Measures Used to Alleviate Heat Stress Appropriate to Reduce Ammonia Emissions?

Barbara Scherllin-Pirscher [1], Christian Mikovits [2,3], Kathrin Baumann-Stanzer [4], Martin Piringer [4] and Günther Schauberger [2,*]

1 Regional Office Styria, Central Institute for Meteorology and Geodynamics, 8054 Graz, Austria
2 WG Environmental Health, Department of Biomedical Sciences, University of Veterinary Medicine, 1210 Vienna, Austria
3 Institute for Sustainable Economic Development, University of Natural Resources and Life Sciences, 1180 Vienna, Austria
4 Department of Environmental Meteorology, Central Institute for Meteorology and Geodynamics, 1190 Vienna, Austria
* Correspondence: gunther.schauberger@vetmeduni.ac.at; Tel.: +43-699-81199157

Abstract: The emission of ammonia (NH_3) is predominantly caused by agriculture, especially by livestock keeping. The health effects of NH_3 and the related formation of particulate matter are the reasons for solid efforts to reduce their ambient concentrations. In addition, the impact of global warming on livestock is increasing due to heat stress, likely also increasing NH_3 emissions. Therefore, adaptation measures are under discussion to reduce the heat stress of animals inside livestock units. Because of the relationship between temperature increase and NH_3 release, the impact of the adaptation measures to cool the indoor air of livestock units (three different energy-saving air preparation systems, an inversion of the feeding and resting times by half a day, a reduction of the stocking density and doubling the maximum volume flow rate) was investigated. The NH_3 release was calculated by the following predictors: indoor air temperature; ventilation rate describing the turbulence inside the livestock building; and the diurnal variation caused by the animal activity. These parameters were calculated by a simulation model for the indoor climate of livestock buildings. The monthly mean of the NH_3 emission for several adaptation measures, which were applied to reduce heat stress, were compared with the emission of a reference building for 1800 fattening pigs, divided into nine sections with 200 animals each for an all-in-all-out production cycle to calculate the mitigation potential. The higher the cooling power of such adaptation measures, the higher the mitigation potential for NH_3. In particular, those adaptation measures which cool the inlet air (e.g., cooling pads reduce the emission by −2%, earth-air heat exchangers by −3.1%) show the best performance to mitigate the NH_3 emission of livestock buildings.

Keywords: ammonia (NH_3); global warming; animal husbandry; heat stress; mitigation measures; fattening pigs

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1. Introduction

Ammonia (NH_3) and particulate matter ((PM) fine solid particles, and liquid droplets) are pollutants with implications on the environment, which range from the acidification of terrestrial and the eutrophication of aquatic environments, to impacts on biodiversity in general [1]. Further aspects are the direct implications on animals [2] and human health [3]. The most-reported acute implications of NH_3 exposure for both are nasal lavage (liquid acquired from the nose), lung function and bronchial responsiveness, eye, nose, and throat irritation, headache, nausea, diarrhoea, hoarseness, sore throat, cough, chest tightness, nasal congestion, palpitations, shortness of breath, stress, drowsiness, and alterations in mood [4,5]. NH_3 is an important precursor of fine particulate matter formation in the atmosphere [6–10]. It is important to highlight the link between $PM_{2.5}$ and NH_3 emissions.

Between 30% and 50% of all $PM_{2.5}$ is a direct result of NH_3 emissions [11–13]. In 1990, nitrogen accounted for 30% of global $PM_{2.5}$ formation, increasing to 39% in 2013 [14]. It was found that a reduction of NH_3 emissions by 50% leads to a 24% reduction of total $PM_{2.5}$ concentrations during winter, mainly driven by the reduced formation of ammonium nitrate [15]. NH_3 is one of the airborne pollutants, which cannot be reduced in a comparable amount to many other European pollutants, such as SO_2 in the 1980s. Thus, for Europe, it has been shown that NH_3 emissions have dropped by 23% between 1990 and 2015, although between 2014 and 2015, emissions increased by 1.8% [16]. Between 2000 and 2015, the emissions decreased by 8%. In Austria, however, a positive trend (an increase of NH_3 emissions from 1990 to 2016 by +3%) was observed [17].

In Austria, most NH_3 emissions are caused by agricultural activities (95%), with 47% for livestock and manure storage, 43% for manure spreading, 8% for fertiliser, and 2% for pasture and other activities. Overall, about 62 kt NH_3 were emitted in 2011 [18]. The Austrian emission was 57.2 kt in 2005, with a continuous increase to 64.6 kt in 2017. According to the National Emissions Reduction Commitments (NEC guideline) [19], a reduction of 12.3% should be achieved in 2020 (in relation to 2017) to reach the goal of 50.3 kt. For 2020 the emission was determined with 65.42 kt in reality. For all years from 2020 to 2029, the EU will have to reduce its total NH_3 emissions by 6% compared with 2005, and by 19% for all years from 2030 onwards [17].

All negative impacts of the ambient concentrations of NH_3 and the related secondary $PM_{2.5}$ formation are human premature deaths and health-related expenses [3,20–23]. For the EU, about 274,000 premature deaths per year, i.e., 6% of all deaths, are due to exposure to $PM_{2.5}$ and ozone [24]. On the basis of the human premature death rate, the threshold for the annual risk exposure level for $PM_{2.5}$ was downward adjusted to 2.4–5.9 $\mu g/m^3$ from a previous level of 5.8 to 8.8 $\mu g/m^3$ [25].

In the EU, the cost range for damages due to NH_3 emissions lie between EUR 70 and 320 billion, equivalent to EUR 150–750 per capita, of which about 75% are related to health damage and air pollution. Related to NH_3, the mean costs for the EU are estimated at EUR 9.5/kg NH_3 with a high variation in between the countries (countries with the three highest and four lowest costs (EUR/kg NH_3) are: Belgium 36, Luxembourg 30, The Netherlands 27; Lithuania 2, Finland 3, Estonia 3, Ireland 3. For Europe, the health costs from secondary ammonium particles were estimated at EUR 2–20/kg nitrogen [22]. For China, the societal benefits of a 50% reduction of NH_3 emissions with costs of USD 6–11 billion were estimated to amount to USD 18–42 billion [26]. The marginal abatement cost of ammonia emission is only 10% of that of nitrogen oxides emission globally to mitigate $PM_{2.5}$ air pollution [14].

Since NH_3 emissions have been shown to be climate sensitive, with NH_3 emissions increasing with increasing ambient temperatures, the global change effect cannot be neglected in the future. An empirical estimate suggests that an assumed warming of 5 K would increase NH_3 emissions by 42% on average (in a range of 28% to 67%, [27]). The impact of climate change (warming of 0.23 K per decade inside livestock buildings) on the NH_3 emissions of livestock buildings was estimated to increase by 1.6% per decade [28]. Using long-term climate simulations, Geels et al. [29] showed that the climate change impact on NH_3 emissions and resulting secondary aerosol formation will increase chronic mortality by up to 4% until 2080. This means that the expected global warming will counteract the efforts to reduce agriculturally emitted NH_3 to improve air quality. For the 2050s, the NH_3 emissions from confined livestock buildings, predominantly used for fattening pigs and poultry, are expected to increase by about 15 to 20% (relative to 2007) due to the increase in temperature [30]. Skjøth and Geels [31] investigated the sensitivity of agricultural NH_3 emission categories due to global warming, showing the highest sensitivity for livestock buildings and manure storage, manure handling, the application of fertiliser, and grazing animals. They expect an emission increase up to 40% due to the global warming signal.

Under the assumption of a constant linear trend of anthropogenic warming until 2050, NH_3 emissions from livestock buildings will increase by about 11% between 1981 and 2050.

For the storage of manure, Aarnink and Elzing [32] found a 10% increase of the emission rate of NH_3 for an increase of the storage temperature of 1 K.

The release of NH_3 can be modified by several predictors. The following predictors are closely related to the keeping of animals: physical activity with a distinct diurnal variation; the size of the defecation area, which is the main release surface; the nitrogen content of the feed; the bedding material; and the pH value of manure [26,33–39]. Some of these predictors can be directly used to mitigate the NH_3 release, e.g., reducing the size of the fouling surface by offering a well-accepted and comfortable solid lying area, or by a restricted dietary crude protein content.

The main microclimatic predictors for the NH_3 release are temperature, the air velocity above the release surface, and the ventilation regime inside the livestock building [40–45]. These predictors are closely connected to the indoor microclimate of the livestock building. Measures which alleviate heat stress (HS) can lead to a side-effect by reducing the NH_3 emission. Cooling the inlet air can lead to a reduction of the ventilation rate from the livestock building [46].

Tremendous efforts will be needed in the upcoming decade to reduce the NH_3 emission from agricultural activities in a proposed range of about 25%. In this respect, we analyse the potential of selected adaptation measures, which alleviate HS inside livestock buildings for fattening pigs (body mass 30 to 120 kg, mechanically ventilated) to also reduce the NH_3 emission. With a simulation driven by meteorological data (1981 to 2017), the indoor climate and the related release of NH_3 are calculated for a reference building on a business-as-usual basis, and compared to that of seven adaptation measures to reduce heat stress.

2. Data and Methods

2.1. Simulation of the Indoor Climate of Confined Livestock Buildings

Meteorological data are needed on an hourly basis (air temperature and relative humidity) for the calculation of the indoor climate and the related emissions of odorous substances and NH_3. The Austrian Meteorological Service ZAMG (Zentralanstalt fürMeteorologie und Geodynamik, Vienna, Austria) provided measurements for the weather station close to the city of Wels (48.16° N, 14.07° E) for the time period 1981 to 2017.

The simulation of the indoor climate was performed by a steady-state model developed by Schauberger et al. [47,48], which calculates the thermal indoor parameters (air temperature, humidity) and the ventilation flow rate. The simulation is driven only by meteorological data. The thermal environment inside the building depends on the livestock (sensible and latent heat release), the thermal properties of the building (sensible heat loss), and the ventilation system and its control unit, which controls the ventilation rate by means of the indoor air temperature as the control parameter. The ventilation system is characterised by the minimum ventilation rate (wintertime, to ensure not only the required air quality but also to avoid cold stress) and the maximum ventilation rate (summertime, to remove the sensible heat of the animals to prevent HS). The core of the model is based on the sensible heat balance of a livestock building [46–49]. The model calculations were performed for a representative livestock building for fattening pigs (body mass between 30 and 120 kg, mechanically ventilated) in central Europe for 1800 heads, divided into nine sections with 200 animals each for an all-in-all-out production cycle. This conventional livestock building for fattening pigs used as a business-as-usual scenario is called reference building REF. Fattening pigs were selected because they are more sensitive to heat stress than piglets and are a relevant source for NH_3 in the national inventory in the range of 17% [18].

The seven adaptation measures to reduce HS for the animals were applied to the entire livestock building with 1800 pigs. The outcome of the simulation of the seven adaptation measures was compared to that of the reference building REF.

2.2. Ammonia Emission and the Mitigation Potential

In general, the airborne NH_3 emission rate of a livestock building is calculated by a body mass-specific emission factor $e_{0,}$ which is related to one animal place (AP). The reference NH_3 emission rate is an annual mean value with $e_{NH3,0}$ = 3.64 kg a^{-1} per AP, which is selected from the German VDI standard [50].

The NH_3 release is modified by the indoor climate (temperature, ventilation rate, and time of the day) of the livestock building [42,44]. This modification is considered by the release modification factor R according to $e = e_0\, R$. R is calculated on the basis of the indoor air temperature T_i, the ventilation rate V, and the physical activity of animals as a function of daytime t [28,44,49]. The release modification factor R is thus given by:

$$R = \exp(0.0314(T_i - T_R))V_n^{0.318}\left(1 + 0.25\sin\left(\frac{2\pi}{24h}(t-6h)\right) + \frac{0.25}{3}\sin\left(\frac{2\pi}{24h}3(t-6h)\right)\right)$$

with the indoor temperature T_i (°C), the reference temperature T_R = 20 °C, the normalised ventilation rate $V_n = V/V_d$, calculated by the ventilation rate per animal place V, normalised to unity by V_d = 200 $m^3\ h^{-1}$ per AP, and the time of the day t. The ventilation rate V and the indoor temperature T_i are calculated by the indoor simulation. The factor R is calculated on an hourly basis and aggregated to monthly mean values. The relative modification of the NH_3 emission MOD of a certain adaptation measure (AM) is calculated by the monthly mean of the release modification factor R_i of this AM and the release modification factor R_{REF} for the reference case REF, with a business-as-usual scenario according to $MOD_i = 1 - R_i/R_{REF}$. or as a percentage $MOD_i = 100\ (1 - R_i/R_{REF})$.

2.3. Adaptation Measures to Reduce Heat Stress

In total, seven AMs are investigated. First, three different energy-saving air preparation systems [51] comprising: (1) direct evaporative cooling by cooling pads (CP); (2) an indirect evaporative cooling by the combination of cooling pads with a regenerative heat exchanger (CPHE) to reduce the humidity load caused by the evaporative cooling; and (3) an earth-air heat exchanger (EAHE), using the ground as heat storage. The fourth AM assumes an inversion of the feeding and resting times by half a day to move the maximum heat release of the animals to night-time with a lower inlet air temperature INV. Two further AMs modify the internal heat load of the livestock building by a reduction of the stocking density (SD) to (5) 80% of the design value (SD80%) and (6) to 60% (SD60%). The last AM (7) affects the design value of the ventilation system by doubling the maximum volume flow rate (VENT) to increase the removal of the sensible heat released by the animals. Technical details on all seven AMs are discussed in Schauberger et al. [52].

3. Results

The primary goal of the seven AMs is the reduction of HS. The efficacy of HS reduction as a ratio of the heat stress of a certain AM, and the reference scenario REF, is shown in Figure 1, displaying the annual sums of the HS parameter P_{T25} for the reference scenario REF and all seven AMs. The HS parameter P_{T25} gives the portion of time (h/a) above the threshold value of T = 25 °C. The slope of a specific AM goes proportional to the reduction factor. The flatter the regression, the higher the efficacy. For the line of identity, the indoor situation is identical to the HS inside the reference building without an AM, which means that no reduction of HS can be expected. The best performance is shown for the energy-saving air preparation AMs for cooling the inlet air (EAHE, CP, and CPHE) followed by doubling the ventilation rate VENT, the inversion of the resting and activity periods INV and the reduction of the stocking density SD60% and SD80%.

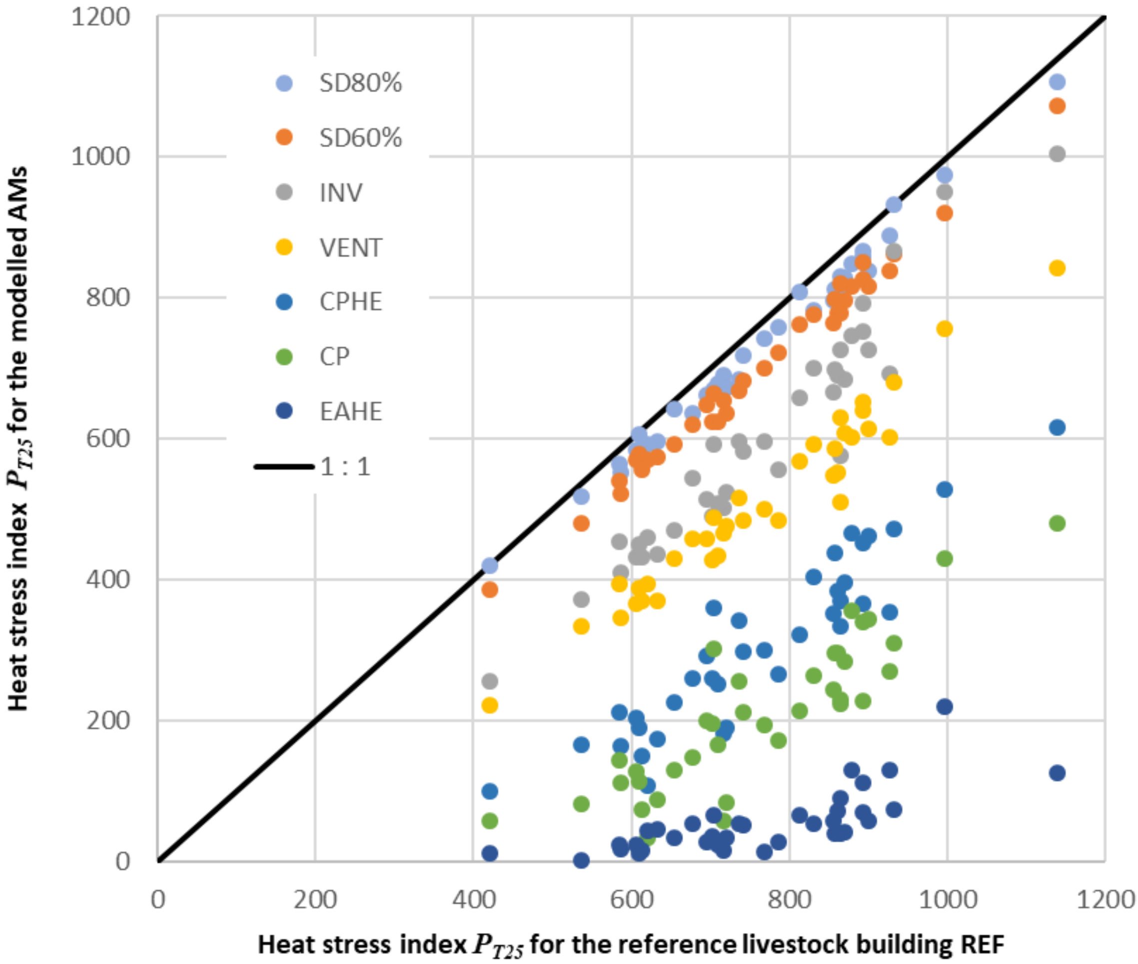

Figure 1. Efficacy of heat stress reduction by the use of AMs shown by the exceedance frequency P_{T25} (h/a) for an indoor temperature threshold of 25 °C as an HS index. Adaptation measures: stocking density SD80%; stocking density SD60%; inversion of the resting and activity periods INV; doubling the ventilation rate VENT; cooling pads and heat exchanger CPHE; cooling pads CP; and earth-air heat exchanger EAHE [53].

Even if the HS index P_{T25} quantifies the performance of the AMs with respect to HS, the modification of the indoor climate for the entire year is not represented by this value. Therefore, the two parameters, indoor air temperature and volume flow rate of the ventilation system, were selected to describe the indoor climate for all months. These two parameters are also predictors for the NH_3 release. The volume flow rate is used as a proxy for the air velocity close to the release surface for NH_3. The third predictor is animal activity, which does not show any dependence from the indoor climate.

The difference of the monthly mean indoor temperature over a year between the reference building REF and the seven AMs is shown in Figure 2. Due to the fact that the temperature difference is analysed, the trend over the 37 years of simulation is widely eliminated. SD80% and INV show almost no reduction of indoor temperature during summer, followed by a slight decrease by SD60%. The temperature reduction for the energy-saving air preparation measures (CP, CPHE, and EAHE) is distinctly higher for the summer months compared to the other AMs except for VENT. VENT shows a similar summertime temperature reduction to CP and CPHE but less variation. EAHE indicates not only a reduction of the indoor air temperature in summer but also an increase during wintertime, caused by the use of the soil as a heat source. The annual mean value of the temperature difference is shown in the lowest right graph. This demonstrates the considerable variation of temperature differences for the EAHE scenario again.

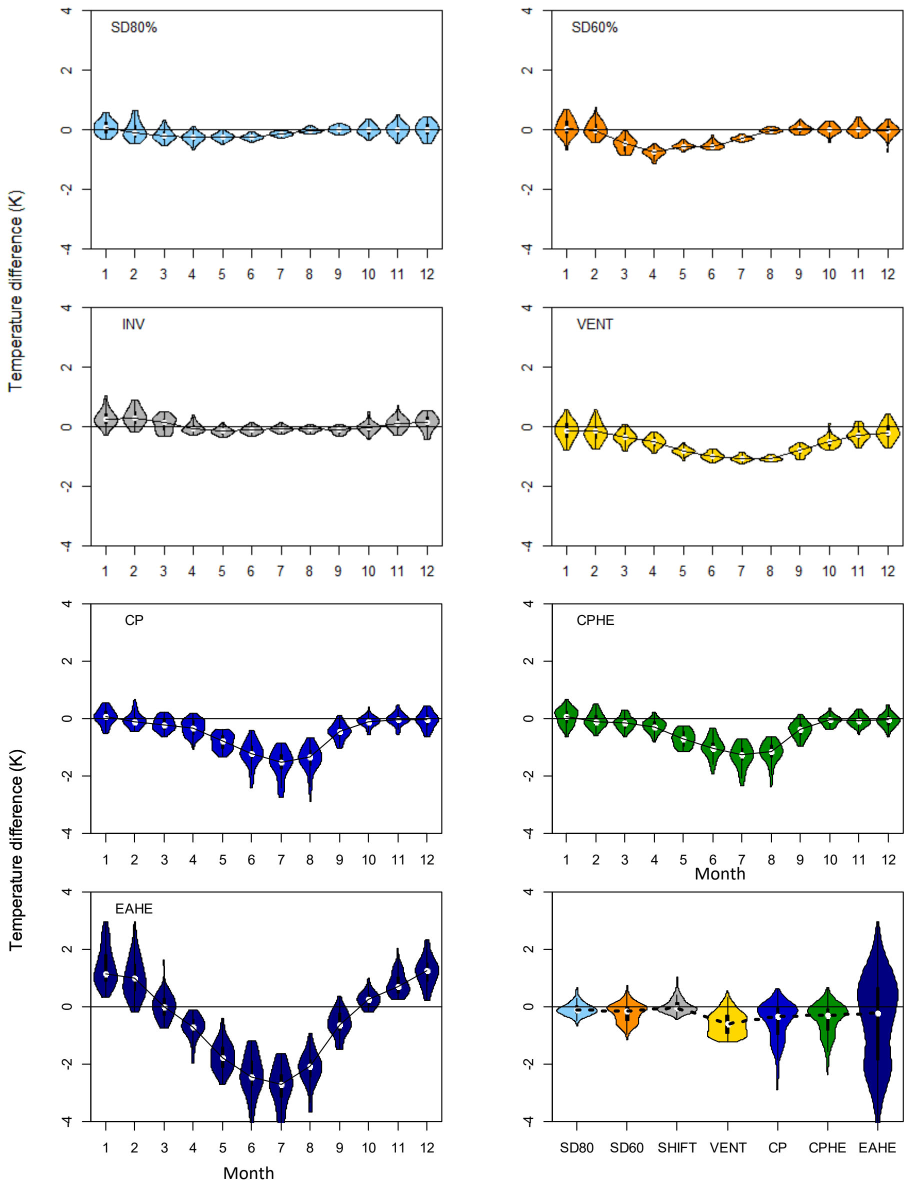

Figure 2. Violin plot of the difference of the monthly mean values (period 1981–2017) of the indoor temperature for a specific AM relative to the reference building REF. Adaptation measures: stocking density SD80%; stocking density SD60%; inversion of the resting and activity periods INV; doubling the ventilation rate VENT; cooling pads CP; cooling pads and heat exchanger CPHE; and earth-air heat exchanger EAHE. The annual mean values of the temperature differences (black dashed line), as well as their intra-annual spread, are shown in the lowest right graph.

In Figure 3, the difference of the ventilation rate per animal place between the reference building REF and the application of the AMs is shown. During summertime, the slight reduction of the heat release of the animals by SD80% and SD60% also causes a slight decrease of the ventilation rate. If INV and especially VENT are used to reduce HS, the ventilation rate per animal place is increased during the summer months. CP and CPHE show only an increase in the summertime ventilation rate variability compared to the winter months without a specific trend. Using EAHE, the warming of the inlet air during wintertime causes an increase of the ventilation rate. This side effect causes an amelioration of the air quality. The reduction of the ventilation rate difference to the REF scenario during the summer months is caused by the fact that the sensible heat release of the animals is reduced, which causes an abatement of the ventilation rate as well.

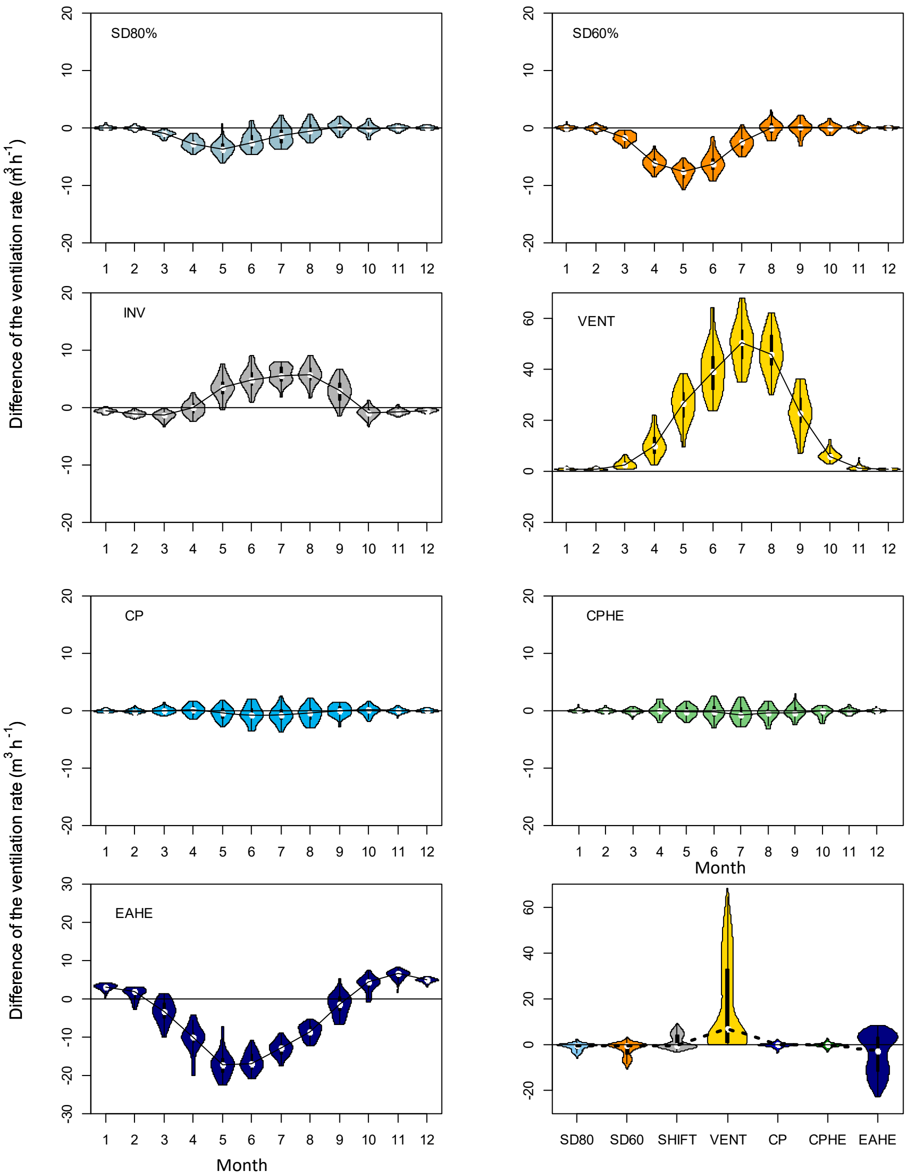

Figure 3. Violin plot of the difference of the ventilation rate per animal place ($m^3\ h^{-1}$) of the monthly mean values (period 1981–2017) of a specific AM relative to the reference building REF: stocking density SD80%; stocking density SD60%; inversion of the resting and activity periods INV doubling the ventilation rate VENT; cooling pads (CP); cooling pads and heat exchanger CPHE; and earth-air heat exchanger EAHE. The annual mean values of the ventilation rate difference (black dashed line), as well as their intra-annual spread, are shown in the lowest right graph. Note different y-axis ranges for VENT, EAHE, and the annual mean chart.

The relative modification of the NH_3 emission *MOD* (monthly mean values for the period 1981–2017) caused by the two predictors indoor air temperature and volume flow rate, is depicted in Figure 4. *MOD* is shown by colour-coded data points with red for a relative increase of ammonia emission and blue for a reduction. For all AMs, both an increase and a decrease in NH_3 emissions can occur. For SD80%, SD60%, INV, and VENT, the difference in the ventilation rate has a more significant impact on the NH_3 emission than the indoor air temperature difference. Therefore, the highest variation of NH_3 emissions is found for VENT. For CP and CPHE, the variation in NH_3 emissions is dominated by the indoor air temperature differences. The widest spread of NH_3 emissions is found for the EAHE, equally caused by both predictors: A temperature increase of up to 3 K for wintertime and a decrease of about -4 K for summertime (Figure 2), an increase of the ventilation rate of about 8 $m^3\ h^{-1}$ for wintertime (due to higher inlet air temperature) and a decrease of –22 $m^3\ h^{-1}$ for summertime due to lower inlet air temperature (Figure 3). These characteristics of the EAHE result in a decrease of the NH_3 emission of 19% for the summer months due to a lower indoor temperature (Figure 2) and a lower ventilation flow rate (Figure 3), and an increase of up to 14% for the winter months caused by a higher indoor temperature and a corresponding higher ventilation flow rate (Figure 5).

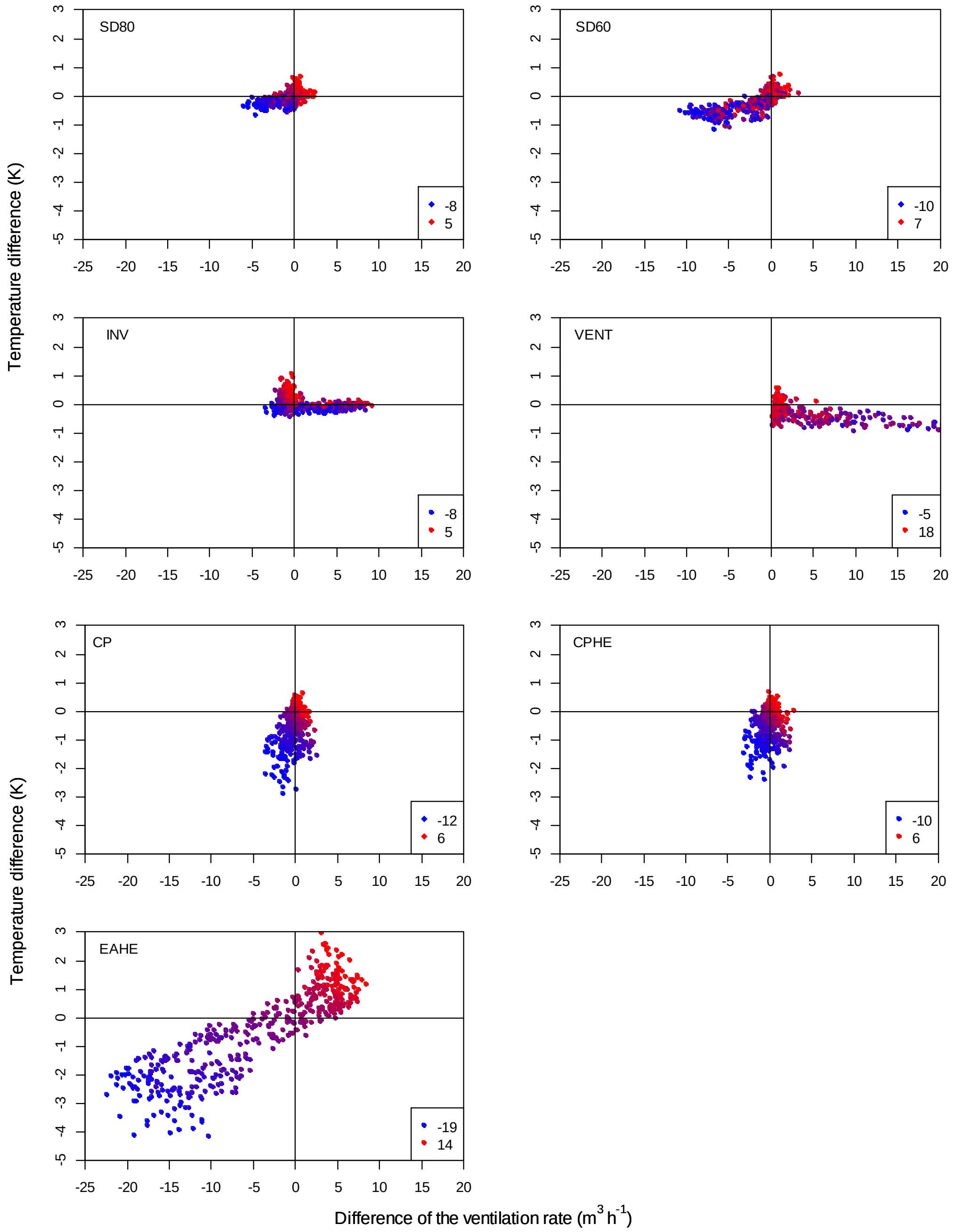

Figure 4. Scatterplot of monthly mean values (period 1981–2017) of the relative modification of the NH_3 emission MOD (blue: decrease; red: increase) depending on the indoor temperature difference (K) and the difference of the ventilation rate per animal place ($m^3\ h^{-1}$) between a specific AM and the reference building REF. The numbers in each plot give the maximum decrease (in blue) and increase (in red) of MOD. Adaptation measures: stocking density SD80%; stocking density SD60%; inversion of the resting and activity periods INV; doubling the ventilation rate VENT; cooling pads CP; cooling pads and heat exchanger CPHE; and earth-air heat exchanger EAHE.

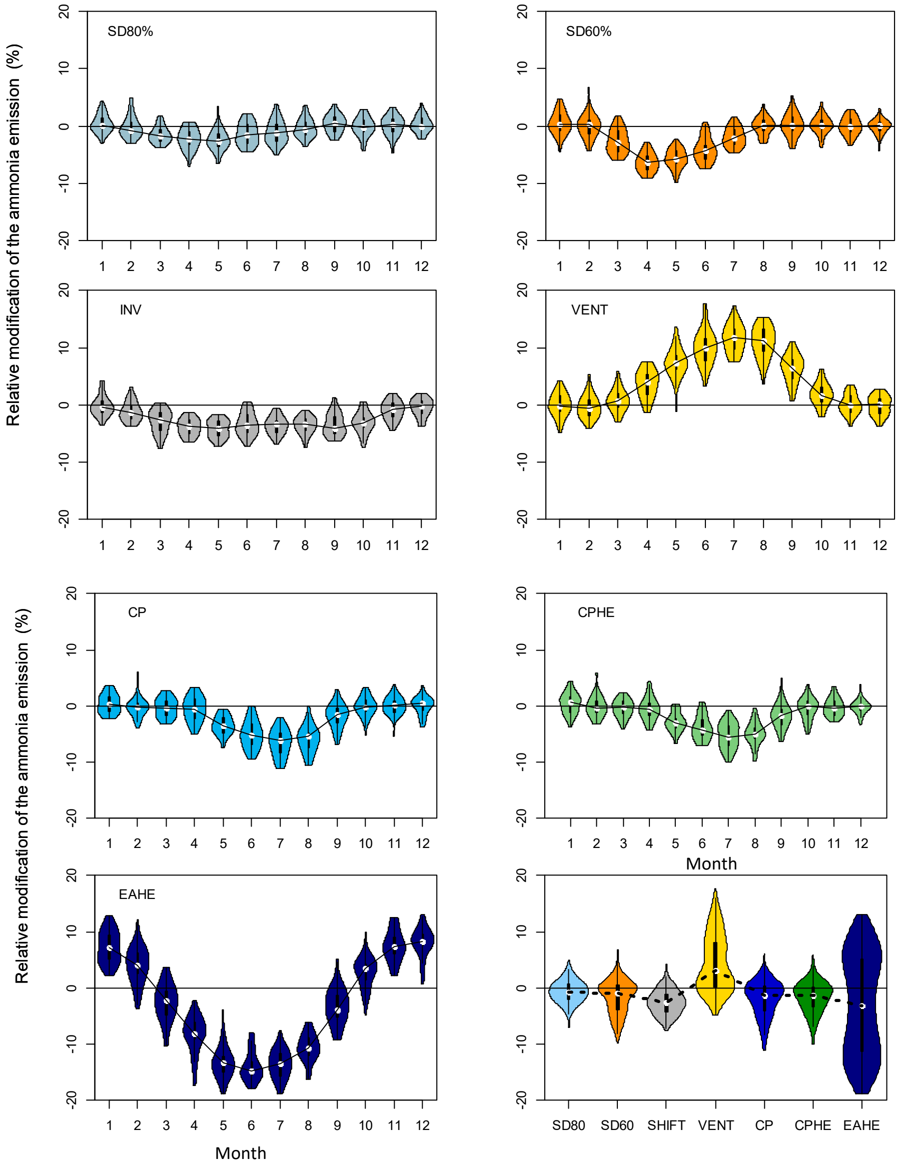

Figure 5. Violin plot of the relative modification of the NH_3 emission *MOD* (%) of the monthly mean values (period 1981–2017) for a specific AM and the reference building REF for all months and as an annual man value. Adaptation measures: stocking density SD80%; stocking density SD60%; inversion of the resting and activity periods INV; doubling the ventilation rate VENT; cooling pads CP and cooling pads and heat exchanger CPHE; and earth-air heat exchanger EAHE. The annual mean values of the relative difference of the ammonia emission (black dashed line), as well as their intra-annual spread, are shown in the lowest right graph.

In Figure 5, the relative difference in the ammonia emission between the REF scenario and a specific AM is shown in the form of violin plots as a time course over the months. Most of the AMs show a reduction of the NH_3 emission, especially for the spring and summer months. VENT and EAHE show a distinct increase for some of the months. The growth of the NH_3 emission by VENT is caused by the rise of the air velocity close to the release surface of NH_3 (e.g., slatted floor, slurry surface) during the summer months. During the cold period, the ventilation rate stays unchanged (see Figure 3, VENT), which means that the mean of the NH_3 emission shows no change as well. The increase of the ventilation rate during the warm season results in a growth of the yearly mean of the NH_3 emission of 4.3% (Table 1).

Table 1. Descriptive statistics (maximum, 3rd quartile, median, mean, 1st quartile and minimum) of the relative modification of the NH_3 emission *MOD* (%) between the reference building REF and the application of the seven AMs (stocking density SD80%, stocking density SD60%, inversion of the resting and activity periods INV, doubling the ventilation rate VENT, cooling pads CP, cooling pads and heat exchanger CPHE, and earth-air heat exchanger EAHE). A reduction of the ammonia release is highlighted in bold.

	Relative Ammonia Difference (%)						
	SD80%	**SD60%**	**INV**	**VENT**	**CP**	**CPHE**	**EAHE**
Maximum	5.0	6.9	4.3	17.6	6.0	5.8	13.0
3rd Quartile	0.6	0.4	**−1.1**	8.1	0.4	0.2	5.1
Median	**−0.7**	**−0.9**	**−2.7**	3.1	**−1.4**	**−1.3**	**−3.2**
Mean	**−0.7**	**−1.7**	**−2.6**	4.3	**−2.0**	**−1.7**	**−3.1**
1st Quartile	**−2.1**	**−3.9**	**−4.2**	0.1	**−4.0**	**−3.4**	**−11.4**
Minimum	**−7.1**	**−9.9**	**−7.7**	**−4.9**	**−11.1**	**−10.0**	**−19.0**

The EAHE causes a higher indoor air temperature (Figure 2, EAHE) and a higher ventilation rate during the cold season (Figure 3, EAHE). This results in a higher NH_3 emission during the cold season as well. This increase is compensated by the efficacy of the cooling during summertime. The EAHE shows the highest NH_3 reduction of all AMs by a mean value over the year of −3.1% (Table 1).

All AMs except VENT reduce the mean NH_3 emission between −0.7% (SD80%) and −3.1% (EAHE).

4. Discussion

The release of NH_3 by a surface inside livestock buildings can be described by models, which use a gradient between the surface and air concentration and a convective mass transfer coefficient [54]. The parameterisation of this coefficient for livestock buildings is performed for nearly all approaches by air temperature and air velocity (e.g., dairy [40], layers [55], pigs [56], and manure [43,57,58]). For the NH_3 emission due to the storage and spreading of manure, and also the dry matter content, pH, and the proportion of N/NH_4, are relevant predictors [59]. These parameters can only be included in a parameterisation on farm level. The NH_3 release inside the livestock building depends on the air temperature, the air velocity close to the release surface, and the activity of the animals e.g., [40,43,44,60–62]. These parameters are related to meteorological parameters, depending on the ventilation system (mechanically or naturally ventilated), the stocking rate, and the thermal properties of the building [47–49]. Gyldenkærne et al. [42] calculated the release modification factor for livestock buildings (about 34% of the NH_3 emissions) by a power function, with an exponent b by $R \sim T_i v_i^b$ with the indoor air temperature T_i and the air velocity v_i close to the surface where NH_3 is released. These two parameters can be calculated by a simple parameterisation [63] or by more sophisticated simulation models [28,46]. Besides the indoor air temperature and air velocity, the animal activity should be considered as a predictor for the diurnal variation of the release modification factor. The temporal trend of the NH_3 emission due to global warming shows a relative increase of 0.16% per year. However, following the clean air endeavour between 1990 and 2015, emissions over that period were reduced by 23% in Europe. The global warming signal is counteracting this reduction in the range of 4% during this period, which means that the overall decrease for ammonia emission was only 19%. For Austria, with a global warming increase of 1% from 1990 to 2015, this gives an increase in emissions of 5% instead [28].

Due to the commitment of the EU regulation to reduce NH_3 emissions until 2030, several abatement techniques are under discussion. Besides the storage of manure and its application on fields, the emission of the livestock building causes about 2/3 of the

NH_3 emission of pigs. Many techniques show a wide range of reduction factors and corresponding costs [23,64–71]. Most of these reduction techniques propose a restriction of the size of the NH_3 release surface on animal level (e.g., living zone, dunging area) and for manure storage, permanent cleaning of the animal area, and cooling of the manure. To reduce the emission in the outlet air from mechanically ventilated livestock buildings, end-of-pipe systems are also in use. Acid scrubbers can achieve an emission reduction close to 100% and bio-scrubbers have an average ammonia removal of 70% [72–74]. The outlet air purification is limited to mechanically ventilated buildings, with the highest costs compared to other mitigation measures, showing declining costs with growing livestock [23,75].

Due to global warming, AMs are applied to alleviate heat stress inside livestock buildings. These AMs can be grouped into measures including energy-saving air treatment systems, which cool the inlet air (e.g., cooling pads, earth-air heat exchanger), the use of certain building elements (e.g., insulation), optimising building characteristics (e.g., spatial orientation), the modification of the indoor climate at the animal level (e.g., fogging, cooling the drinking water, increasing air velocity), and the adaptation of livestock management (e.g., the reduction of stocking density) [53]. Due to the fact that indoor air temperature is a major predictor for NH_3 emission, some of these AMs can be assumed as feasible to mitigate NH_3 emission. In this study, only those AMs were investigated, which can be handled by a simulation model of the indoor climate of a livestock building [52]. It turned out that those AMs that cool the inlet air (especially CP and CPHE) not only decrease the indoor air temperature best (Figure 2) and do not change the ventilation rate much (Figure 3), but they also reduce the NH_3 emission to quite an extent (Figure 5). The EAHE, in contrast, causes a higher indoor air temperature (Figure 2, EAHE) and a higher ventilation rate during the cold season (Figure 3, EAHE). This results in a higher NH_3 emission during the cold season as well. This increase is, however, compensated by the efficacy of the cooling during summertime. The EAHE shows the highest NH_3 reduction of all AMs by a mean value over the year of −3.1% (Table 1). INV is second in reducing the NH_3 emission (−2.6%, Table 1) but shows a comparatively low reduction of summertime indoor air temperatures (Figure 2) and an increase in summertime ventilation rates (Figure 3). SD60% and SD80% are less effective in reducing the NH_3 emission. VENT is different from all other AMs in that it shows an increase of the air velocity close to the release surface of NH_3 during the summer months, causing a yearly mean increase of the NH_3 emission of 4.3% (Table 1).

Besides such simulation models, empirical studies were performed. Pertagnol [76] investigated cooling pads, high-pressure fogging systems, and a modified earth-air heat exchanger, and found a reduction of the NH_3 emission of 29%, 28%, and 20%, respectively. These reductions were calculated only for those days with an outdoor air temperature above 22 °C. For the entire year, the decline of the NH_3 emission is in general lower by 24%, 31%, and 14%. Jeppsson et al. [77] found a NH_3 reduction between 29% and 49% for showers for fattening pigs. The following reasons were discussed for this reduction: (1) reduced indoor air temperature; (2) a scrubber effect by wet surfaces; and (3) reduced pen fouling and partly a dilution of urine on the slatted area and on the surface of the slurry. The last two aspects are not included in the simulation model of this study. The empirical investigations show a higher reduction compared to the simulated values. The AM, which uses a doubling of the ventilation rate, causes an increase of NH_3 emission in the mean. Other AMs which use additional fans to increase the air velocity close to the animals (forced ventilated livestock buildings, e.g., boost, circulation fans, or hybrid ventilation systems) will cause a similar effect.

The detected reduction of NH_3 emissions by cooling systems should be considered in the decision process. In this respect, all systems, which increase the air velocity inside livestock buildings, should be avoided (e.g., additional fans). This study is a valuable example that not only the isolated effect of animal health and animal welfare should be considered, but also aspects of environmental protection and the related human health as part of the "One Health" concept [78,79].

5. Conclusions

Due to global warming, the application of AMs to alleviate HS inside livestock buildings is becoming more and more common. We postulated that the AMs selected for this study will also contribute to a reduction of NH_3 emissions. To determine the NH_3 release, the modification by the indoor climate (temperature, ventilation rate, and the animal activity by the time of the day) was taken into account. Monthly mean values of the NH_3 release for the reference case REF, a representative livestock building for fattening pigs (body mass between 30 and 120 kg, mechanically ventilated) for central Europe for 1800 heads, were calculated and compared to the values obtained by seven selected AMs. The time period spans the years 1981 to 2017. The results reveal quite an ambiguous picture; for all AMs investigated, both an increase and a decrease in NH_3 emissions compared to REF were found, although on average, a decrease between −0.7 and −3.1% was calculated. For those adaptation measures which cool the inlet air, the highest NH_3 reduction was found with −3.1% for EAHE, −1.3% for CPHE, and −1.4% for CP.

The only exception is VENT, which shows an increase of 4.3%. This is caused by the increased air velocity inside livestock buildings, and thus all AMs applying this feature should be avoided.

So, in principle, the postulation is fulfilled, i.e., an alleviation in HS inside livestock buildings is accompanied by a reduction of NH_3. AMs that cool the inside air (CP, CPHE, EAHE) are to be preferred over those reducing the stocking density (SD80%, SD60%) or increasing the ventilation rate (VENT). An inversion of the feeding and resting times by half a day to move the maximum heat release of the animals to night-time (INV) is comparably successful as CP or CPHE. In practice, the costs will also determine which AM is going to be applied to improve the well-being of the animals.

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References

1. Leip, A.; Billen, G.; Garnier, J.; Grizzetti, B.; Lassaletta, L.; Reis, S.; Simpson, D.; Sutton, M.A.; De Vries, W.; Weiss, F.; et al. Impacts of European livestock production: Nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. *Environ. Res. Lett.* **2015**, *10*, 115004. [CrossRef]
2. Ni, J.Q.; Erasmus, M.A.; Croney, C.C.; Li, C.; Li, Y. A critical review of advancement in scientific research on food animal welfare-related air pollution. *J. Hazard. Mater.* **2020**, *408*, 124468. [CrossRef]
3. Giannadaki, D.; Giannakis, E.; Pozzer, A.; Lelieveld, J. Estimating health and economic benefits of reductions in air pollution from agriculture. *Sci. Total Environ.* **2018**, *622*, 1304–1316. [CrossRef]
4. Sundblad, B.-M.; Larsson, B.-M.; Acevedo, F.; Ernstgård, L.; Johanson, G.; Larsson, K.; Palmberg, L. Acute respiratory effects of exposure to ammonia on healthy persons. *Scand. J. Work. Environ. Health* **2004**, *30*, 313–321. [CrossRef]
5. Wing, S.; Wolf, S. Intensive livestock operations, health, and quality of life among eastern North Carolina residents. *Environ. Health Perspect.* **2000**, *108*, 233–238. [CrossRef]

6. Xu, L.; Penner, J. Global simulations of nitrate and ammonium aerosols and their radiative effects. *Atmos. Chem. Phys.* **2012**, *12*, 9479–9504. [CrossRef]
7. Anderl, M.; Haider, S.; Zethner, G.; Kropsch, M.; Pöllinger, A.; Zentner, E. *Maßnahmen zu sekundären Partikeln aus der Landwirtschaft: Ammoniakemissionen*; Umweltbundesamt Wien: Wien, Austria, 2016.
8. Backes, A.; Aulinger, A.; Bieser, J.; Matthias, V.; Quante, M. Ammonia emissions in Europe, part I: Development of a dynamical ammonia emission inventory. *Atmos. Environ.* **2016**, *131*, 55–66. [CrossRef]
9. Backes, A.M.; Aulinger, A.; Bieser, J.; Matthias, V.; Quante, M. Ammonia emissions in Europe, part II: How ammonia emission abatement strategies affect secondary aerosols. *Atmos. Environ.* **2016**, *126*, 153–161. [CrossRef]
10. Spangl, W.; Nagl, C.; Schneider, J.; Kaiser, A. Herkunftsanalyse der PM10-Belastung in Österreich. In *Ferntransport und Regionale Beiträge*; Umweltbundesamt: Wien, Austria, 2006.
11. Wu, Y.; Gu, B.; Erisman, J.W.; Reis, S.; Fang, Y.; Lu, X.; Zhang, X. PM2. 5 pollution is substantially affected by ammonia emissions in China. *Environ. Pollut.* **2016**, *218*, 86–94. [CrossRef]
12. Bauer, S.E.; Tsigaridis, K.; Miller, R. Significant atmospheric aerosol pollution caused by world food cultivation. *Geophys. Res. Lett.* **2016**, *43*, 5394–5400. [CrossRef]
13. Erisman, J.; Schaap, M. The need for ammonia abatement with respect to secondary PM reductions in Europe. *Environ. Pollut.* **2004**, *129*, 159–163. [CrossRef] [PubMed]
14. Gu, B.; Zhang, L.; Dingenen, R.V.; Vieno, M.; Grinsven, H.J.V.; Zhang, X.; Zhang, S.; Chen, Y.; Wang, S.; Ren, C.; et al. Abating ammonia is more cost-effective than nitrogen oxides for mitigating $PM_{2.5}$ air pollution. *Science* **2021**, *374*, 758–762. [CrossRef] [PubMed]
15. Backes, A.M.; Aulinger, A.; Bieser, J.; Matthias, V.; Quante, M. Influence of ammonia emissions on aerosol formation in Northern and Central Europe. In *Air Pollution Modeling and Its Application XXIV*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 29–35.
16. EEA. *European Union Emission Inventory Report 1990–2015 under the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP)*; European Environment Agency: Maastricht, The Netherlands, 2017.
17. EEA. *Air Quality in Europe—2017 Report*; European Environment Agency: Copenhagen, Denmark, 2017.
18. Anderl, M.; Haider, S.; Zethner, G.; Kropsch, M.; Pöllinger, A.; Zentner, E. *Massnahmen zur Minderung sekundärer Partikelbildung durch Ammoniakemissionen aus der Landwirtschaft*; Umweltbundesamt: Wien, Austria, 2016; p. 85.
19. *EU 2016/2284*; Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the Reduction of National Emissions of Certain Atmospheric Pollutants, Amending Directive 2003/35/EC and Repealing Directive 2001/81/EC in 2284. EU: Luxembourg, 2016.
20. Wyer, K.E.; Kelleghan, D.B.; Blanes-Vidal, V.; Schauberger, G.; Curran, T.P. Ammonia emissions from agriculture and their contribution to fine particulate matter: A review of implications for human health. *J. Environ. Manag.* **2022**, *323*, 116285. [CrossRef] [PubMed]
21. Giannakis, E.; Kushta, J.; Bruggeman, A.; Lelieveld, J. Costs and benefits of agricultural ammonia emission abatement options for compliance with European air quality regulations. *Environ. Sci. Eur.* **2019**, *31*, 93. [CrossRef]
22. Brink, C.; van Grinsven, H.; Jacobsen, B.H.; Rabl, A.; Gren, I.-M.; Holland, M.; Klimont, Z.; Hicks, K.; Brouwer, R.; Dickens, R.; et al. Costs and benefits of nitrogen in the environment. In *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives*; Bleeker, A., Grizzetti, B., Howard, C.M., Billen, G., van Grinsven, H., Erisman, J.W., Sutton, M.A., Grennfelt, P., Eds.; Cambridge University Press: Cambridge, UK, 2011; pp. 513–540. [CrossRef]
23. Wagner, S.; Angenendt, E.; Beletskaya, O.; Zeddies, J. Costs and benefits of ammonia and particulate matter abatement in German agriculture including interactions with greenhouse gas emissions. *Agric. Syst.* **2015**, *141*, 58–68. [CrossRef]
24. Lelieveld, J.; Haines, A.; Pozzer, A. Age-dependent health risk from ambient air pollution: A modelling and data analysis of childhood mortality in middle-income and low-income countries. *Lancet Planet. Health* **2018**, *2*, e292–e300. [CrossRef]
25. Cohen, A.J.; Brauer, M.; Burnett, R.; Anderson, H.R.; Frostad, J.; Estep, K.; Balakrishnan, K.; Brunekreef, B.; Dandona, L.; Dandona, R. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015. *Lancet* **2017**, *389*, 1907–1918. [CrossRef]
26. Zhang, X.; Gu, B.; van Grinsven, H.; Lam, S.K.; Liang, X.; Bai, M.; Chen, D. Societal benefits of halving agricultural ammonia emissions in China far exceed the abatement costs. *Nat. Commun.* **2020**, *11*, 4357. [CrossRef]
27. Sutton, M.A.; Reis, S.; Riddick, S.N.; Dragosits, U.; Nemitz, E.; Theobald, M.R.; Tang, Y.S.; Braban, C.F.; Vieno, M.; Dore, A.J.; et al. Towards a climate-dependent paradigm of ammonia emission and deposition. *Philos. Trans. R. Soc. B Biol. Sci.* **2013**, *368*, 20130166. [CrossRef]
28. Schauberger, G.; Piringer, M.; Mikovits, C.; Zollitsch, W.; Hörtenhuber, S.J.; Baumgartner, J.; Niebuhr, K.; Anders, I.; Andre, K.; Hennig-Pauka, I.; et al. Impact of global warming on the odour and ammonia emissions of livestock buildings used for fattening pigs. *Biosyst. Eng.* **2018**, *175*, 106–114. [CrossRef]
29. Geels, C.; Andersson, C.; Hänninen, O.; Lansø, A.S.; Schwarze, P.E.; Skjøth, C.A.; Brandt, J. Future premature mortality due to O_3, Secondary inorganic aerosols and primary PM in Europe—Sensitivity to changes in climate, anthropogenic emissions, population and building stock. *Int. J. Environ. Res. Public Health* **2015**, *12*, 2837–2869. [CrossRef] [PubMed]
30. Simpson, D.; Andersson, C.; Christensen, J.H.; Engardt, M.; Geels, C.; Nyiri, A.; Posch, M.; Soares, J.; Sofiev, M.; Wind, P.; et al. Impacts of climate and emission changes on nitrogen deposition in Europe: A multi-model study. *Atmos. Chem. Phys.* **2014**, *14*, 6995–7017. [CrossRef]

31. Skjøth, C.A.; Geels, C. The effect of climate and climate change on ammonia emissions in Europe. *Atmos. Chem. Phys.* **2013**, *13*, 117–128. [CrossRef]
32. Aarnink, A.J.A.; Elzing, A. Dynamic model for ammonia volatilization in housing with partially slatted floors, for fattening pigs. *Livest. Prod. Sci.* **1998**, *53*, 153–169. [CrossRef]
33. Jaderborg, J.P.; Spiehs, M.J.; Woodbury, B.L.; DiCostanzo, A.; Parker, D.B. Use of Bedding Materials in Beef Bedded Manure Packs in Hot and Cool Ambient Temperatures: Effects on Ammonia, Hydrogen Sulfide, and Greenhouse Gas Emissions. *Trans. ASABE* **2021**, *64*, 1197–1209. [CrossRef]
34. Wulf, S.; Roesemann, C.; Eurich-Menden, B.; Grimm, E. Minderung von Ammoniakemissionen in der Landwirtschaft—Anforderungen, Potenziale und Umsetzbarkeit. In Proceedings of the 14. KTBL-Tagung: Aktuelle Rechtliche Rahmenbedingungen für die Tierhaltung, Ulm/Hannover, Germany, 24–26 September 2019.
35. Groenestein, C.; Hutchings, N.; Haenel, H.; Amon, B.; Menzi, H.; Mikkelsen, M.; Misselbrook, T.; van Bruggen, C.; Kupper, T.; Webb, J. Comparison of ammonia emissions related to nitrogen use efficiency of livestock production in Europe. *J. Clean. Prod.* **2019**, *211*, 1162–1170. [CrossRef] [PubMed]
36. Opderbeck, S.; Keßler, B.; Gordillio, W.; Schrade, H.; Piepho, H.-P.; Gallmann, E. Influence of a cooled, solid lying area on the pen fouling and lying behavior of fattening pigs. *Agriculture* **2020**, *10*, 307. [CrossRef]
37. Aarnink, A.J.A.; Keen, A.; Metz, J.H.M.; Speelman, L.; Verstegen, M.W.A. Ammonia Emission Patterns during the Growing Periods of Pigs Housed on Partially Slatted Floors. *J. Agric. Eng. Res.* **1995**, *62*, 105–116. [CrossRef]
38. Le, P.D.; Aarnink, A.J.A.; Jongbloed, A.W. Odour and ammonia emission from pig manure as affected by dietary crude protein level. *Livest. Sci.* **2009**, *121*, 267–274. [CrossRef]
39. Van Harn, J.; Aarnink, A.J.A.; Mosquera, J.; Van Riel, J.W.; Ogink, N.W.M. Effect of bedding material on dust and ammonia emission from broiler houses. *Trans. ASABE* **2012**, *55*, 219–226. [CrossRef]
40. Ding, L.; Li, Q.; Wang, C.; Zhang, G.; Jiang, R.; Yu, L.; Zheng, W.; Gao, R.; Ma, W.; Zhang, S.; et al. Determination of the mass transfer coefficient of ammonia emissions from dairy open lots using a scale model. *Biosyst. Eng.* **2020**, *190*, 145–156. [CrossRef]
41. Saraz, O.; Alexander, J.; Ferreira Tinoco, I.d.F.; Gates, R.S.; Rocha, O.; Sullivan, K.; Zapata Marín, O.L. A simple methodology to measure ammonia flux generated in naturally ventilated poultry houses. *Rev. Colomb. Cienc. Pecu.* **2015**, *28*, 3–12.
42. Gyldenkærne, S.; Skjøth, C.A.; Hertel, O.; Ellermann, T. A dynamical ammonia emission parameterisation for use in air pollution models. *J. Geophys. Res. D Atmos.* **2005**, *110*, D07108.1–D07108.14. [CrossRef]
43. Ni, J. Mechanistic models of ammonia release from liquid manure: A review. *J. Agric. Eng. Res.* **1999**, *72*, 1–17. [CrossRef]
44. Schauberger, G.; Lim, T.T.; Ni, J.Q.; Bundy, D.S.; Haymore, B.L.; Diehl, C.A.; Duggirala, R.K.; Heber, A.J. Empirical model of odor emission from deep-pit swine finishing barns to derive a sstandardised odor emission factor. *Atmos. Environ.* **2013**, *66*, 84–90. [CrossRef]
45. Blunden, J.; Aneja, V.P.; Westerman, P.W. Measurement and analysis of ammonia and hydrogen sulfide emissions from a mechanically ventilated swine confinement building in North Carolina. *Atmos. Environ.* **2008**, *42*, 3315–3331. [CrossRef]
46. Mikovits, C.; Zollitsch, W.; Hörtenhuber, S.J.; Baumgartner, J.; Niebuhr, K.; Piringer, M.; Anders, I.; Andre, K.; Hennig-Pauka, I.; Schönhart, M.; et al. Impacts of global warming on confined livestock systems for growing-fattening pigs: Simulation of heat stress for 1981 to 2017 in Central Europe. *Int. J. Biometeorol.* **2019**, *63*, 221–230. [CrossRef]
47. Schauberger, G.; Piringer, M.; Petz, E. Separation distance to avoid odour nuisance due to livestock calculated by the Austrian odour dispersion model (AODM). *Agric. Ecosyst. Environ.* **2001**, *87*, 13–28. [CrossRef]
48. Schauberger, G.; Piringer, M.; Petz, E. Steady-state balance model to calculate the indoor climate of livestock buildings, demonstrated for fattening pigs. *Int. J. Biometeorol.* **2000**, *43*, 154–162. [CrossRef]
49. Schauberger, G.; Piringer, M.; Heber, A.J. Odour emission scenarios for fattening pigs as input for dispersion models: A step from an annual mean value to time series. *Agric. Ecosyst. Environ.* **2014**, *193*, 108–116. [CrossRef]
50. Verein Deutscher Ingenieure VDI. *VDI 3894 Part 1. Emissions and Immissions from Animal Husbandry—Housing Systems and Emissions—Pigs, Cattle, Poultry, Horses*; Beuth: Berlin, Germany, 2011.
51. Vitt, R.; Weber, L.; Zollitsch, W.; Hörtenhuber, S.J.; Baumgartner, J.; Niebuhr, K.; Piringer, M.; Anders, I.; Andre, K.; Hennig-Pauka, I.; et al. Modelled performance of energy saving air treatment devices to mitigate heat stress for confined livestock buildings in Central Europe. *Biosyst. Eng.* **2017**, *164*, 85–97. [CrossRef]
52. Schauberger, G.; Mikovits, C.; Zollitsch, W.; Hörtenhuber, S.J.; Baumgartner, J.; Niebuhr, K.; Piringer, M.; Knauder, W.; Anders, I.; Andre, K.; et al. Global warming impact in confined livestock buildings: Efficacy of adaptation measures to reduce heat stress for growing-fattening pigs. *Clim. Chang.* **2019**, *156*, 567–587. [CrossRef]
53. Schauberger, G.; Hennig-Pauka, I.; Zollitsch, W.; Hörtenhuber, S.J.; Baumgartner, J.; Niebuhr, K.; Piringer, M.; Knauder, W.; Anders, I.; Andre, K.; et al. Efficacy of adaptation measures to alleviate heat stress in confined livestock buildings in temperate climate zones. *Biosyst. Eng.* **2020**, *200*, 157–175. [CrossRef]
54. Ni, J.Q.; Heber, A.J.; Sutton, A.L.; Kelly, D.T. Mechanisms of gas releases from swine wastes. *Trans. ASABE* **2009**, *52*, 2013–2025.
55. Tong, X.; Zhao, L.; Heber, A.J.; Ni, J.Q. Development of a farm-scale, quasi-mechanistic model to estimate ammonia emissions from commercial manure-belt layer houses. *Biosyst. Eng.* **2020**, *196*, 67–87. [CrossRef]
56. Ni, J.Q.; Hendriks, J.; Vinckier, C.; Coenegrachts, J. Development and validation of a dynamic mathematical model of ammonia release in pig house. *Environ. Int.* **2000**, *26*, 105–115. [CrossRef]

57. Sommer, S.G.; Olesen, J.E. Effects of dry matter content and temperature on ammonia loss from surface-applied cattle slurry. *J. Environ. Qual.* **1991**, *20*, 679–683. [CrossRef]
58. Ye, Z.; Zhu, S.; Kai, P.; Li, B.; Blanes-Vidal, V.; Pan, J.; Wang, C.; Zhang, G. Key factors driving ammonia emissions from a pig house slurry pit. *Biosyst. Eng.* **2011**, *108*, 195–203. [CrossRef]
59. Anderson, N.; Strader, R.; Davidson, C. Airborne reduced nitrogen: Ammonia emissions from agriculture and other sources. *Environ. Int.* **2003**, *29*, 277–286. [CrossRef]
60. Bjerg, B.; Norton, T.; Banhazi, T.; Zhang, G.; Bartzanas, T.; Liberati, P.; Cascone, G.; Lee, I.B.; Marucci, A. Modelling of ammonia emissions from naturally ventilated livestock buildings. Part 1: Ammonia release modelling. *Biosyst. Eng.* **2013**, *116*, 232–245. [CrossRef]
61. Jeppsson, K.-H. Diurnal variation in ammonia, carbon dioxide and water vapour emission from a deep litter house for fattening pigs. In Proceedings of the International Symposium Gaseous and Odor Emissions from Animal Production Facilities, Horsens, Denmark, 1–4 June 2003.
62. Tabase, R. *Impact of Ventilation on Ammonia and Odour Emissions from Pig Housing*; Gent University: Gent, Belgium, 2020.
63. Skjøth, A.C.; Hertel, O.; Gyldenkærne, S.; Ellermann, T. Implementing a dynamical ammonia emission parameterisation in the large-scale air pollution model ACDEP. *J. Geophys. Res. D Atmos.* **2004**, *109*, D06306.
64. Economic Commission for Europe, Executive Body for the Convention on Long-range Transboundary Air Pollution. UN ECE/EB.AIR/120. In *Guidance Document on Preventing and Abating Ammonia Emissions from Agricultural Sources*; Economic Commission for Europe, Executive Body for the Convention on Long-range Transboundary Air Pollution: Geneva, Switzerland, 2014.
65. United Nations Economic Commission for Europe. UN ECE/EB.AIR/129. In *Framework Code for Good Agricultural Ractice for Reducing Ammonia Emissions*; United Nations Economic Commission for Europe: Geneva, Switzerland, 2015.
66. Wulf, S.; Rösemann, C.; Eurich-Menden, B.; Grimm, E. Ammoniakemissionen in der Landwirtschaft Minderungsziele und -potenziale. In Proceedings of the Aktuelle Rechtliche Rahmenbedingungen für die Tierhaltung, Hannover, Germany, 31 May 2017.
67. Amann, M.; Klimont, Z.; Winiwarter, W. *Emissions from Agriculture and their Control Potentials*; DG-Environment of the European Commission: Brussels, Belgium, 2012.
68. De Vries, J.W.; Melse, R.W. Comparing environmental impact of air scrubbers for ammonia abatement at pig houses: A life cycle assessment. *Biosyst. Eng.* **2017**, *161*, 53–61. [CrossRef]
69. Rößler, R.; Eurich-Menden, B.; Vandré, R.; Wulf, S.; Döhler, H. Ammonia emissions: Abatement costs for feeding of fattening pigs. *Landtechnik* **2012**, *67*, 69–72.
70. Döhler, H.; Vandré, R.; Rößler, R.; Eurich-Menden, B.; Wulf, S. Ammonia emissions: Abatement costs for the storage of liquid manure. *Landtechnik* **2011**, *66*, 465–468.
71. Döhler, H.; Vandré, R.; Rößler, R.; Wulf, S. Ammonia emissions: Abatement costs for the application of liquid manure. *Landtechnik* **2011**, *66*, 469.
72. Melse, R.W.; Ogink, N.W.M. Air scrubbing techniques for ammonia and odor reduction at livestock operations: Review of on-farm research in the Netherlands. *Trans. Am. Soc. Agric. Eng.* **2005**, *48*, 2303–2313. [CrossRef]
73. Melse, R.W. *Air Treatment Techniques for Abatement of Emissions from Intensive Livestock Production*; Wageningen University: Wageningen, The Netherlands, 2009.
74. Van der Heyden, C.; Demeyer, P.; Volcke, E.I.P. Mitigating emissions from pig and poultry housingfacilities through air scrubbers and biofilters: State-of-the-art andperspectives. *Biosyst. Eng.* **2015**, *134*, 74–93. [CrossRef]
75. Fritz, C. Abluftreinigung in der Mastschweinehaltung—Eine betriebswirtschaftliche Betrachtung für Österreich. In Proceedings of the Bautagung Raumberg-Gumpenstein 2019, Irdning-Donnersbachtal, Austria, 15–16 May 2019; p. 12.
76. Pertagnol, J. *Untersuchung zu verschiedenen Zuluftführungs-und Kühlungsmöglichkeiten in Mastschweineställen*; Universität Hohenheim: Hohenheim, Germany, 2013.
77. Jeppsson, K.H.; Olsson, A.C.; Nasirahmadi, A. Cooling growing/finishing pigs with showers in the slatted area: Effect on animal occupation area, pen fouling and ammonia emission. *Livest. Sci.* **2021**, *243*, 104377. [CrossRef]
78. Queenan, K.; Garnier, J.; Rosenbaum Nielsen, L.; Buttigieg, S.; De Meneghi, D.; Holmberg, M.; Zinsstag, J.; Rüegg, S.; Häsler, B.; Kock, R. Roadmap to a One Health agenda 2030. In *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*; CABI: Wallingford, UK, 2017; Volume 12, pp. 1–17.
79. Tarazona, A.M.; Ceballos, M.C.; Broom, D.M. Human relationships with domestic and other animals: One Health, One Welfare, One Biology. *Animals* **2020**, *10*, 43. [CrossRef]