Supporting Information

Concentrations and emissions of particulate matter from intensive pig production at a large farm in north China

Wen Xu[1], Kun Zheng[1], Lingmin Meng[1], Xuejun Liu[1*], Eberhard Hartung[2], Marco Roelcke[3], Fusuo Zhang[1]

[1]*College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China*
[2]*Institute of Agricultural Engineering, University of Kiel, Olshausenstrasse 40, 24098 Kiel, Germany*
[3]*Institute of Geoecology, Technische Universität Braunschweig, Langer Kamp 19c, 38106 Braunschweig, Germany*

[*] Corresponding author: liu310@cau.edu.cn; Tel: +86 10 62733459; Fax: +86 10 62731016

Text S1. Climatic Conditions and Pig Growth Characteristics

The two pig houses selected were both designed to use natural ventilation without additional heating or cooling. The climatic conditions inside and outside the houses and the ventilation rate per house for all monitoring periods are presented in **Table S1,** together with the number and average weight of the fattening pigs. During the whole experimental period over both houses, the indoor temperature averaged 26.4 ± 2.9°C with a maximum of 31.6°C and a minimum of 19.3°C; relative humidity (RH) averaged 60.1 ± 20.9% with a maximum of 94% and a minimum of 23.2%. The outdoor conditions averaged 17.8±10.3°C (maximum of 31.1°C and minimum of -4.8°C) and 54.6% ±17.9% RH (maximum of 93.2% and minimum of 11.6%). The variations in temperature and relative humidity inside the houses followed those outside, but outdoor climate had a limited impact on indoor climate due to sufficient air exchange. The average weight of each pig is lower in house I during autumn 2010 and in the house II during spring 2011, as compared to other seasons. This is not surprising because the pigs were placed in the houses approximately 6 and 9 weeks from the beginning of the second and third fattening periods, respectively. In addition, some pigs with similar weight (about 20 kg) were brought into the houses on different dates at early stages of the fattening periods, which can also reduce the average weight of the pigs.

The mean ventilation rate per pig per monitoring period varied between 16.1 and 293.4 m^3/h-pig (or between 97.1 and 1735.2 m^3/h-LU). The barn ventilation rates (average of two barns) were highest in summer (232.2 m^3/h-pig or 1487.9 m^3/h-LU), resulting from 100% opening of all windows to control the indoor temperature. In winter, windows on both sides of the barn remained 100% closed. Consequently, the ventilation rates in winter were, on average, 90% lower than those in summer. The relatively large standard deviation which occurred during both spring and autumn was mainly due to different adjustment measures for indoor temperature within a season (discussed mentioned in **Section Site Description**). Compared to the average ventilation rates of fattening barns using a mechanical ventilation system reported by Seedorf *et al*. (1998) in a European study (110-795 m^3/h/LU), the average ventilation rates in this study were notably higher for fattening periods starting in spring months, but within that range for fattening period starting in the autumn months.

Reference

Seedorf, J., Hartung, J., Schroder, M., Linkert, K.H., Pedersen, S., Takai, H., et al. (1998). A survey of ventilation rates in livestock buildings in Northern Europe. J. Agr. Eng. Res. 70: 39-47.

Text S2. Calculation of total heat loss, sensible and latent heat, and heat balance

In the present study the total heat loss Φ_{tot} in W for fattening pigs at 20 °C is expressed as follows (CIGR, 2002):

$$\Phi_{tot} = 5.09m^{0.75} + (1-(0.47+0.003m))(n\times5.09m^{0.75}-5.09m^{0.75}) \qquad (1)$$

where m is the live mass in kg, n is the daily feed energy intake, expressed as n times the maintenance requirement ($5.09m^{0.75}$).

When the temperature was different from 20 °C, the total heat loss Φ^{*}_{tot} in W was calculated with a temperature correction, using the following equation (CIGR, 1984):

$$\Phi^{*}_{tot} = \Phi_{tot}(4\times10^{-5}(20-t)^{3}+1) \qquad (2)$$

where t is the air temperature in °C.

Pigs lose heat as sensible heat due to the temperature gradient between their body temperature and the surrounding air, and as latent heat by evaporation from the respiratory tract. The equations for calculation of sensible Φ^{*}_{sen} and latent Φ^{*}_{lat} heat production in W at house level for fattening pigs can be presented as follows (CIGR, 1984):

$$\Phi^{*}_{sen} = (0.8-1.85\times10^{-7}(t+4)^{4})\Phi^{*}_{tot} \qquad (3)$$

$$\Phi^{*}_{lat} = \Phi^{*}_{tot} - \Phi^{*}_{sen} \qquad (4)$$

Due to dry feed and average floor in our studying fattening houses, a correction k_s (0.95) for the sensible heat production in W at house level was introduced in Pedersen *et al*. (1998) for that adjustment [Eqn (5)]. The adjusted latent heat L in W can then be calculated by Eqn (6):

$$S = k_s\Phi^{*}_{sen} \qquad (5)$$

$$L = \Phi^{*}_{tot} - S \qquad (6)$$

In the present study the pig house was designed to use natural ventilation without supplementary heating. The heat balance can be expressed by Eqn (7):

$$k_s n S = AU\Delta t + Vc\Delta t \qquad (7)$$

where k_s is the correction factor for sensible heat, n is the number of housed pigs, A is the surface area of the pig buildings, m^2, U is the heat transmission coefficient for each building surface, W/m^2-K, Δt is the temperature different between indoors and outdoors, K, V is the ventilation rate, m^3/h and c is the specific heat of air, J/m^3-K.

References

CIGR. (1984). Climatization of animal houses. Commission Internationale du Génie Rural. Report of Working Group. Scottaspress Publishers Limited, Aberdeen.

CIGR. (2002). 4th Report of working group on climatization of animal houses.Heat and moisture production at animal and house level. In: Pedersen, S., Sällvik, K (Eds.), Danish Institute of Agricultural Sciences, Horsens, Denmark.

Pedersen, S., Takai, H., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H. et al. (1998). A Comparison of Three Balance Methods for Calculating Ventilation Ratesin Livestock Buildings. J. Agr. Eng. Res.70:25–37.

Table captions

Table S1. Environmental parameters, ventilation rates and pig growth characteristics of the fattening houses. Data in parenthesis are standard deviations.

Table S2. Data comparison between previous reports and the present study for indoor TSP and PM_{10}.

Table S3. Mean mass concentrations in $\mu g/m^3$ of gases and ions inside and outside the fattening pig houses (numbers in parenthesis are standard deviations; n denotes numbers of samples used for analysis of particulate ions).

Table S4. Correlation coefficients (R^2) between molar concentrations of NH_4^+, NO_3^-, SO_4^{2-} and Cl^- in TSP and PM_{10}.

Table S5. Mean (± standard deviation) molar ratio of aerosol components (NH_4^+, NO_3^-, SO_4^{2-} and Cl^-), calculated from daily mean concentrations in TSP and PM_{10} inside and outside the fattening pig houses

Table S1. Environmental parameters, ventilation rates and pig growth characteristics of the fattening houses. Data in parenthesis are standard deviations.

Site	Monitoring period		
	Summer 2010 6/2-8/31	Autumn 2010 9/15-11/30	Winter 2010/11 12/1-1/7
Fattening house I			
Indoor mean temperature (°C)	28.7 (1.8)	23.7 (1.5)	21.0 (1.5)
Indoor mean relative humidity (%)	76.7 (14.9)	62.9 (11.3)	46.6 (21.3)
Outdoor mean temperature (°C)	26.8 (2.8)	11.5 (7.4)	0.1 (4.2)
Outdoor mean relative humidity (%)	68.3 (15.3)	54.8 (13.9)	30.9 (2.1)
Mean ventilation rate (m^3/h-pig)	171.1 (85.4)	85.8 (155.8)	16.1 (3.3)
Mean ventilation rate (m^3/h-LU)	1078.8 (498.4)	524.4 (708.3)	97.1 (27.5)
Number of pig places	212	296	230
Average weight[a] (kg)	81.4	51.1	86.8
	Spring 2011 4/1-5/30	Summer 2011 6/1-8/11	
Fattening house II			
Indoor mean temperature (°C)	25.3 (1.3)	28.6 (1.8)	
Indoor mean relative humidity (%)	36.9 (9.3)	67.9 (18.8)	
Outdoor mean temperature (°C)	19.1(4.6)	26.4 (1.1)	
Outdoor mean relative humidity (%)	39.1 (20.3)	56.6 (8.2)	
Mean ventilation rate (m^3/h-pig)	100.3 (104.4)	293.4 (144.0)	
Mean ventilation rate (m^3/h-LU)	1328.5 (1422.8)	1735.2 (911.6)	
Number of pig places	271	154	
Average weight [a] (kg)	37.5	93.1	

[a] Averaged weight of pigs brought into the house on different dates during the sampling periods.

Table S2. Data comparison between previous reports and the present study for indoor TSP and PM_{10}.

Particulate matter		Units	Reported data		Data in the present study	
			Mean	Range	Mean	Range
Indoor TSP	Concentration	mg/m^3	3.81	0.03-21.04	1.85	0.24-4.5
	Emission	m^3/h-LU [a]	728.2	—	467.5	41.7-1544.4
		mg/h-m^2 [b]	56.1	—	38.6	3.74-114.9
Indoor PM_{10}	Concentration	mg/m^3	0.95	0.02-6.41	0.63	0.13-2.30
	Emission	m^3/h-LU [a]	184.6	—	256.7	19.02-1027.8
		mg/h-m^2 [b]	14.2	—	16.8	1.43-88.1

[a] Based on 500 kg live animal weight.

[b] Assuming live mass (LU) of 0.077 per area (m^2).

Table S3. Mean mass concentrations in μg/m^3 of gases and ions inside and outside the fattening pig houses (numbers in parenthesis are standard deviations; n denotes numbers of samples used for analysis of particulate ions).

			Concentration							
Site	PM	n	NH_3	SO_2	HNO_3	NO_2	NH_4^+	Cl^-	SO_4^{2-}	NO_3^-
Inside house I	TSP	65	2635.1 (566.1)[a]	n.d.[e]	n.d.	n.d.	18.0 (14.3)	5.7 (3.7)	78.4 (77.4)	24.0(23.9)
Outside houseI	TSP	46	169.1 (44.7)[a]	39[b]	1.9[d]	37.6 (15.1)[c]	12.6 (11.6)	2.9 (1.9)	91.8 (90.9)	24.8 (21.5)
Inside houseII	PM_{10}	44	4157.3 (873.1)[a]	n.d.	n.d.	n.d.	11.3 (8.5)	3.5 (3.4)	23.2 (20.4)	24.1 (22.5)
Outside houseII	PM_{10}	18	286.8 (58.7)[a]	39[b]	1.9[d]	37.6 (15.1)[c]	8.1 (7.2)	2.2 (1.4)	20.8(20.4)	20.7 (20.0)

[a]Mean NH_3 concentration inside and outside the fattening pig houses during the same monitoring period reported by Xu *et al*. (2014).

[b]As mean SO_2 concentration outside the pig houses the first half-year mean value for 2010 in an adjacent rural site (Shangzhuang) in Beijing was taken, as reported by the Ministry of Environmental Protection of China (MEPC, 2010).

[c]Mean NO_2 concentration was taken from mean value measured at Shangzhuang during 2007-2009, as reported by Shen *et al*. (2011).

[d]Mean value during 2002-2003 in Beijing, which was sourced from Wu *et al*. (2009).

[e]Not determined.

References

MEPC (Ministry of Environmental Protection of China). (2010). Ambient air quality in major cities in China in the first half year of 2010. Available at: http://www.mep.gov.cn/ (accessed December 2010).

Shen J.L., Liu, X.J., Zhang, Y., Fangmeier, A., Goulding, K., Zhang, F.S. (2011). Atmospheric ammonia and particulate ammonium from agricultural sources in the North China Plain. Atmos. Environ. 45: 5033-5041.

Xu, W., Zheng, K., Liu, X.J., Meng, L.M., Mendoza Huaitalla, R., Shen, J.L. et al. (2014). Atmospheric NH_3 dynamics at a typical pig farm in China and their implications. Atmos. Pollut. Res. 5: 455-463.

Wu, Z.J., Hu, M., Shao, K.S., and Slanina, J. (2009). Acidic gases, NH_3 and secondary inorganic ions in PM_{10} during summertime in Beijing, China and their relation to air mass history. Chemosphere 76: 1028-1035.

Table S4. Correlation coefficients (R^2) between molar concentrations of NH_4^+, NO_3^-, SO_4^{2-} and Cl^- in TSP and PM_{10}.

Site		NO_3^- *vs* NH_4^+	SO_4^{2-} *vs* NH_4^+	Cl^- *vs* NH_4^+	(NO_3^-+SO_4^{2-}) *vs* NH_4^+	(NO_3^-+SO_4^{2-}+Cl^-) *vs* NH_4^+
Inside house I	TSP	0.857**	0.849**	0.109	0.879**	0.778**
Outside house I	TSP	0.871**	0.714**	0.627**	0.791**	0.714**
Inside house II	PM_{10}	0.728**	0.772**	0.234	0.758**	0.648**
Outside house II	PM_{10}	0.634**	0.955**	0.642**	0.945**	0.940**

**Significant at the 0.01 probability level.

Table S5. Mean (± standard deviation) molar ratio of aerosol components (NH_4^+, NO_3^-, SO_4^{2-} and Cl^-), calculated from daily mean concentrations in TSP and PM_{10} inside and outside the fattening pig houses

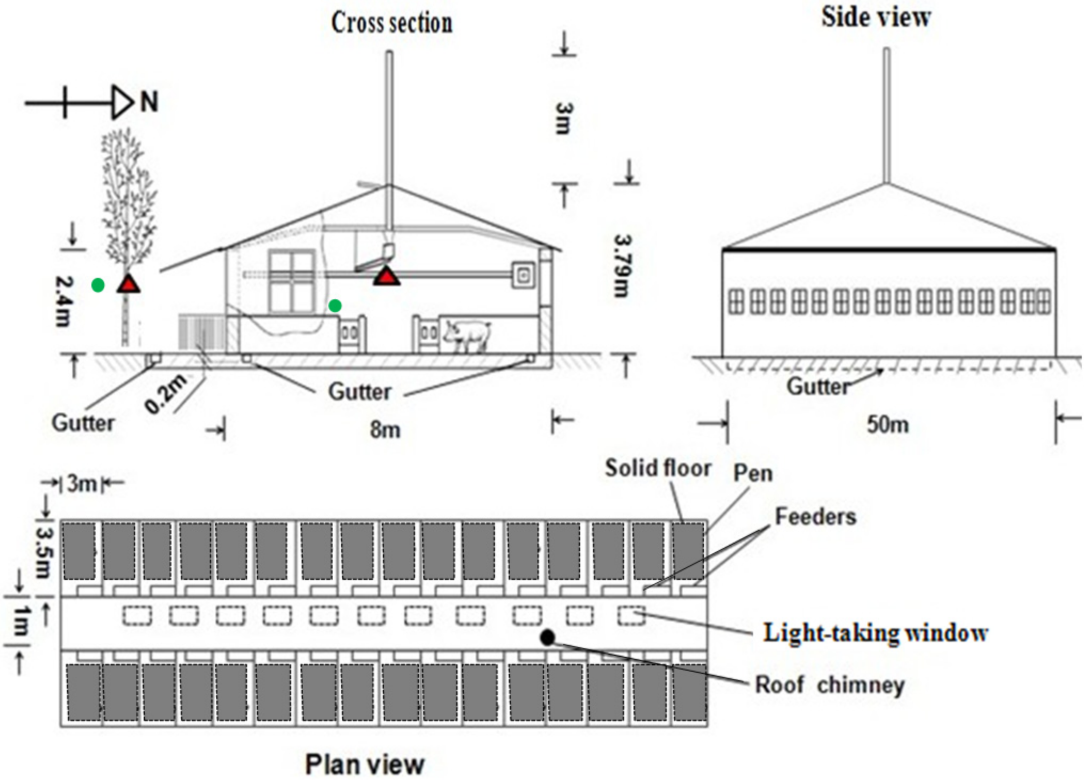
Site		NO_3^-/NH_4^+	Cl^-/NH_4^+	NH_4^+/SO_4^{2-} [a]
Inside house I	TSP	0.37±0.31	0.29±0.29	1.62±1.37
Outside house I	TSP	0.65±0.37	0.28±0.24	0.71±0.90
Inside house II	PM_{10}	0.60±0.92	0.23±0.24	1.64±1.77
Outside house II	PM_{10}	0.64±0.43	0.22±0.21	0.94±1.10

[a] NH_4^+ represents the molar concentration of NH_4^+ that is not combined with NO_3^- (NH_4^+-NO_3^-).

Figure captions

Figure S1. Cross section (left), side view (right), and plan view (bottom) of the fattening pig house with temperature, relatively humidity and particle sampling locations (the red triangles are sampling locations for temperature and relative humidity; the green circles are sampling locations for particulate matter).

Figure S2. Wind rose diagrams of daily mean wind direction and wind speed for sampling periods of a) 2nd Jun-31th August, 2010; b) 15th September-30th November 2010; c)1st December 2010-7th January 2011; d) 1st April-30th May 2011; e) 1st June-11th August, 2011, and the entire experimental period of f) 2nd June 2010-11th August 2011) outside the selected pig farm.



▲ Sampling sites (Temperature and relative humidity)
● Sampling sites (Particulate matter)

Figure 1

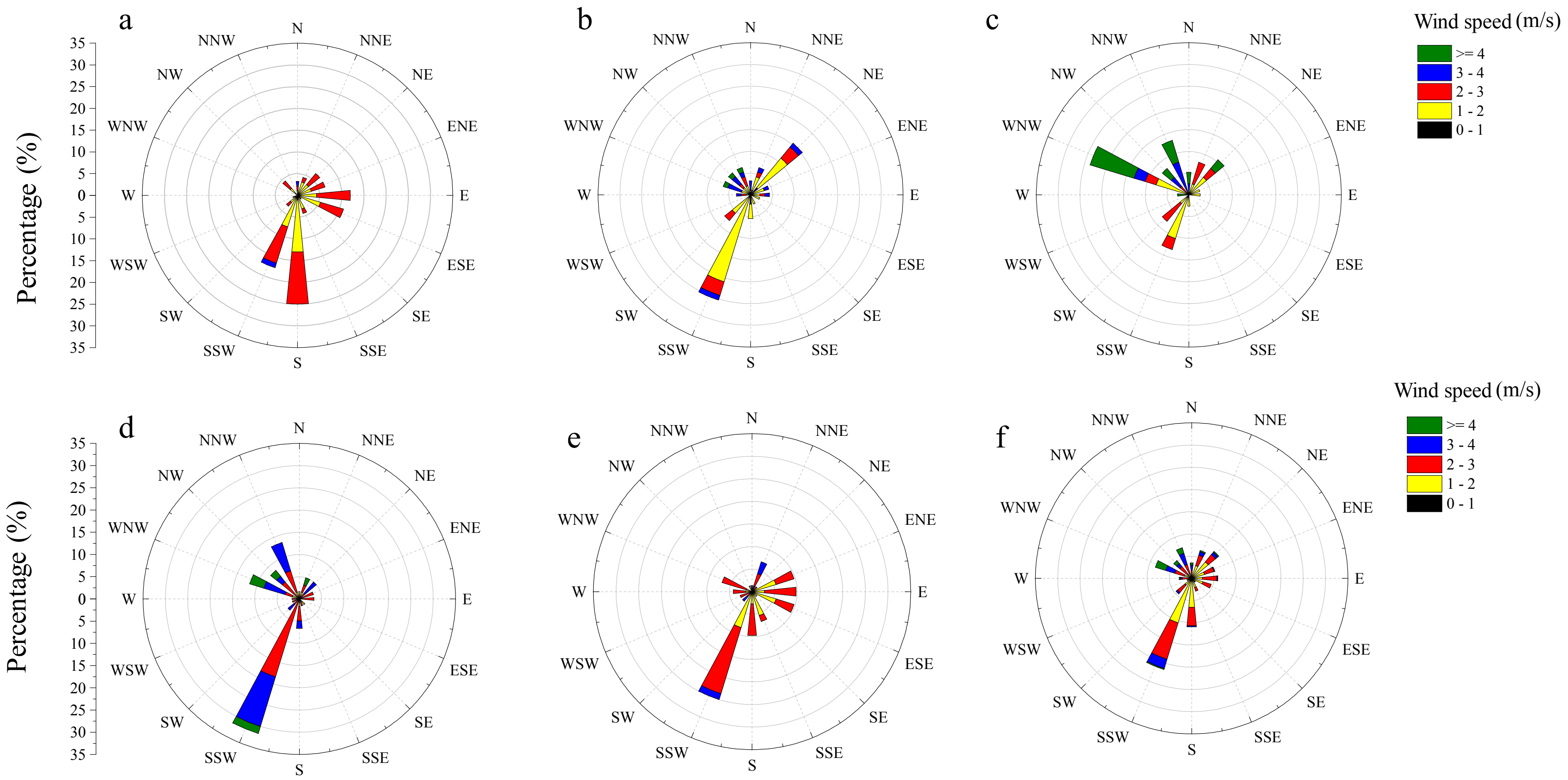

a
b
c
d
e
f
Percentage (%)
35
30
25
20
15
10
5
0
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
Wind speed (m/s)
>= 4
3 - 4
2 - 3
1 - 2
0 - 1

Figure 2