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Global warming impact on confined livestock buildings: efficacy of adaptation measures to reduce heat stress for growing-fattening pigs

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Abstract

Pigs and poultry are predominantly kept in confined livestock buildings with a mechanical ventilation system, insulated building and a high stocking density. These systems are quite sensitive to heat stress which has increased in the last decades from anthropogenic warming. To predict the effect of global warming on the indoor climate of farm animals in such confined livestock buildings, a dataset for 1981 - 2017 of hourly meteorological data was used to analyse the temporal variability and trends for Central Europe, selecting a site north of the Alpine Ridge (Wels, Austria) that well represents Köppen-Geiger class Cfb. The meteorological data drive a simulation model for the indoor climate in a reference building. Seven adaptation measures were selected including three energy saving air preparation systems, the increase of the maximum ventilation rate, the reduction of stocking density, and the shift of the feeding and resting time pattern. The effect of these measures was quantified by the use of several heat stress metrics. The highest reduction of heat stress in comparison to the business as usual reference building was achieved by the three air preparation systems in the range of 74% to 92% for adiabatic systems and 90% and 100% for earth-air heat exchanger, followed by the increase of the ventilation rate, and the time shift. The reduction of the stocking density showed the lowest improvement. Beside the reduction of heat stress, also the temporal trend over three decades was used to quantify the resilience of livestock buildings.

1. Introduction

Pig and poultry production are predominantly kept inside confined livestock buildings, which are often called industrial systems (Gerber et al. 2013). These systems are characterised by a mechanical ventilation system, high stocking density, and insulated buildings. The increase of heat stress of farm animals due to the anthropogenic warming is well known, especially for confined livestock buildings. These global warming effects are not only relevant from an animal welfare perspective but also from an economic point of view.

Rötter and van de Geijn (Rötter and van de Geijn 1999) assumed, that the vulnerability of industrial and confined livestock systems is lower than alternative outdoor systems due to the opportunity of adaptation measures AM. On the other hand, Mikovits et al. (2018) showed for Central Europe that the indoor climate inside confined livestock buildings is more sensitive to heat stress compared to the outdoor situation with increasing trends of the frequency of heat stress over the last three decades. St. Pierre et al. analysed the economic impact of heat stress in the US livestock industry for past climate situations and revealed billion dollar losses with substantial spatial heterogeneity across US regions (St-Pierre et al. 2003). Hence, global warming may affect requirements for the control of thermal conditions of livestock buildings, such as their mechanical ventilation systems (Olesen and Bindi 2002). This calls for AM to reduce the existing as well as the upcoming increase of heat stress. The application of AM will increase the costs (e.g. management, energy, investment) of intensive livestock production, which needs to be balanced to their effects on livestock productivity and animal welfare.

The AM can be divided into two groups. The first group modifies the sensible and latent heat balance of the building by cooling the inlet air, reducing the sensible and latent heat release, and modifying the thermal properties of the building. The second group influences the immediate thermal vicinity of the animals. Examples for such AM are floor cooling (conductive cooling) (Bull et al. 1997; Cabezon et al. 2017; Silva et al. 2009), higher air velocity at animal level to increase the convective heat release (wind-chill effect) (e.g. by tunnel ventilation, booster fans, hybrid ventilation systems (Zhang and Bjerg 2017)), radiative cooling by a cooled cover of the laying zone (Pang et al. 2010), cooled drinking water (Jeon et al. 2006; Renaudeau et al. 2012), wallows (Bracke 2011; de Mello et al. 2017), or water bath (Huynh et al. 2006). The AM of the first group can be evaluated by simulation models at housing level, whereas the second group needs models at animal level, which describe the heat release and the thermal regulation for individual animals.

Most of these AM were investigated by measurements on farm level or for prototypes on laboratory scale with the disadvantage that such measurements can be biased. Biases are caused by the variability of the meteorological situation on a year-to-year basis, the high variability of relevant parameters (e.g. live mass of animals 30 to 120 kg), and the short duration of such measurements over a limited number of fattening periods. Such episodical research activities are often presented in a statistical way. Model approaches using such sources could lead to a more general understanding (e.g. Cooper et al. (1998); Schauberger et al. (1999)).

In our investigation, we selected a steady state simulation model (Mikovits et al. 2018; Schauberger et al. 2000) and applied it to a typical livestock building for growing-fattening pigs in Central Europe. On the basis of such model calculations, the multi-decadal temporal trend of the thermal climate inside livestock buildings can be calculated. It is an indicator of future global warming impacts. The goal of the paper is to estimate the temporal trend of the thermal conditions inside livestock buildings for growing-fattening pigs for a business as usual reference building in relation to heat stress. This situation will be compared to various AM and the related efficacy. The results, particularly on extreme years, should give an orientation, which AM are appropriate to reduce heat stress for growing-fattening pigs under future climate conditions.

2. Materials and Methods

2.1 Meteorological data

For the calculation of the indoor air conditions, like the air temperature and humidity, meteorological data is needed on an hourly basis. The Austrian Meteorological Service ZAMG (Zentralanstalt für Meteorologie und Geodynamik) compiled a reference time series on the basis of representative observational sites around the city of Wels (48.16°N, 14.07°E) for the time period 1981 to 2017 with a temporal resolution of one hour. Following the climate classification of Köppen and Geiger (c.f. Kottek et al. 2006), the station is located within class Cfb (warm temperate, fully humid and warm summer) which is representative for large areas in Central Europe excluding the Alps. Compared to the reference period of 1971-2000 for the whole area of Upper Austria in the future a mean increase of temperature is expected with values of ~+1.4°C (~± 0.5°) until the middle of the century. For the region around Wels the number of summer days (daily maximum temperature ≥ 25°C) will increase from 43.3 days/year by 14.4 additional days (~± 4.5 days/year), hot days (daily maximum temperature ≥ 30°C) is expected to increase in this region from 5.3 days/year, we observe now to between 7 and 13 days/year in the middle of the century. For the same period, the number of tropical nights (minimum temperature ≥ 20°C) will increase from ~0.1 days/year to 1 day/year (~± 0.75 days/year).

2.2 Indoor climate model

The indoor climate was simulated by a steady state model which calculates the thermal indoor parameters (air temperature, humidity) and the ventilation flow rate. The thermal environment inside the building depends on the livestock, the thermal properties of the building, and the ventilation system and its control unit. The core of the model can be reduced to the sensible heat balance of a livestock building (Mikovits et al. 2018; Schauberger et al. 1999; Schauberger et al. 2000). The model calculation were performed for a typical livestock building for fattening pigs for Central Europe for 1800 heads, divided into 9 sections with 200 animals each. The system parameters, which describe the business as usual reference building REF (properties of the livestock, building, and the mechanical ventilation system) are summarised in Tab. 1.

Tab. 1 System parameters for livestock, building, and ventilation system related to one animal place for the indoor climate simulation of the business as usual reference building REF

	Parameter	Value
Animal		
	Body mass m	30-120 kg
	Service period (building emptied for cleaning and disinfection)	10 days
Building		
	Area of the building orientated to the outside (ceiling, walls, windows)	1.41 m^2
	Mean thermal transmission coefficient U weighted by the area of the construction elements (wall, ceiling, door, windows) which are orientated to the outside	0.41 W m^{-2} K^{-1}
Ventilation system		
	Set point temperature of the ventilation control unit, T_C	16 - 20 °C
	Proportional range (band width) of the control unit, ΔT_P	4 K
	Minimum volume flow rate of the ventilation system, V_{min}, for maximum CO_2 concentration 3000 ppm and a body mass m = 30 kg	8.62 m^3 h^{-1}
	Maximum volume flow rate, V_{max}, by maximum temperature difference between indoor and outdoor of 3 K	107 m^3 h^{-1}

For an all in-all out production system AIAO, an animal growth model describes the increase of the release of energy and CO_2 by the growing of the animal body mass of the herd. The time course of the body mass of growing-fattening pigs behaves like a saw tooth wave with a period of 118 d (about 1/3 of a year). These growth periods are superimposed and interact with the time course of the outdoor temperature. To create statistically valid results we calculate the body mass on the basis of a Monte Carlo method, called inverse transform sampling, a useful method for environmental sciences (e.g. Schauberger et al. 2013; Wilks 2011). Details of the method can be found by Mikovits et al. (2018).

2.3 Heat stress measures for growing-fattening pigs

For farm animals, heat stress was quantified by the indoor air temperature (dry bulb) T and the temperature-humidity index THI, and related threshold values X_T and X_{THI}, respectively (Vitt et al. 2017) (Tab. 2).

For a time series with the length t and n equidistant observations of a selected parameter x, the exceedance frequency $P_X = prob\{x | x > X\}$ was defined, given in hours per year (h a^{-1}). The second one describes the exceedance area (area under the curve) A_X calculated according to Thiers and Peuportier (2008) by

$$A_X = \sum_i \left| \begin{array}{lll} x_i - X & \text{for} & x_i > X \\ 0 & \text{for} & x_i \le X \end{array} \right.$$

The area above the threshold X is defined analogously to the degree-days (Gosling et al. 2013), but with the selected parameter x used on an hourly basis instead of daily mean values and results in (Kh/a) for the air temperature and (h/a) for the THI (because THI is dimensionless). All parameters describing heat stress in pigs were calculated as annual sums over the 37 year period (1981-2017) as suggested by Hatfield et al. (2018).

Tab. 2 Heat stress parameters and the related threshold values X (upper limit for specific physiological reactions) for pigs used to evaluate the indoor climate by air temperature T (°C) and temperature-humidity index THI (-) (Vitt et al. 2017).

Heat stress parameter	**Threshold X**
Air temperature T (°C)	X_T = 25°C
Temperature Humidity Index THI THI= 0.72 T_{DB} + 0.72 T_{WB} + 40.6	X_{THI} = 75 alert situation

Dry bulb temperature T_{DB} (= indoor air temperature T); wet bulb temperature T_{WB}

2.4 Model calculations and sensitivity analysis

The model calculations were performed for the entire growing-fattening period for a body mass between 30 and 120 kg. The calculations were done for 1981 to 2017 to determine the trend for the 37 year period. Additionally, we selected the years 1984 and 2003, as one of the coldest and warmest years, respectively, for summertime measured in the last decades, to show specific results outside of the trend calculations.

The trend is estimated with a linear function $x_{trend} = b\ x + a$ for the period 1981 to 2017.

For all seven AM and the selected heat stress parameters air temperature T and THI the mean relative reduction of heat stress R (in %) was calculated for the exceedance frequency P_X and the exceedance area A_X related to the REF system

$$R_{P_X} = 1 - \sum_{i=1981}^{2017} \frac{P_{AM,i}}{P_{REF,i}} \text{ and } R_{A_X} = 1 - \sum_{i=1981}^{2017} \frac{A_{AM,i}}{A_{REF,i}}$$

By the time lag TL in years, the retardation was calculated which can be achieved by a certain AM to keep the heat stress on the level of 1981. The time lag was calculated on the basis of the linear trend

$$TL = \frac{Y_{REF,1981} - Y_{AM,1981}}{k_{AM}}$$

with a certain heat stress parameter (exceedance frequency or exceedance area) for the reference system $Y_{REF,1981}$ and for a certain AM $Y_{AM,1981}$, calculated by the linear trend for 1981 and the slope of the selected AM k_{AM}. The TL was calculated for all seven AM and the four heat stress parameters.

2.5 Adaptation measures

As adaptation measures AM, three different energy saving air preparation systems were calculated (Vitt et al. 2017) using the direct evaporative cooling by cooling pads CP, and indirect evaporative cooling by the combination of cooling pads with a regenerative heat exchanger HE, and an earth-air heat exchanger. Two further AM modify the management of the livestock building by a reduction of the stocking density and corresponding heat release of the livestock during the summer period, and a shift of the diurnal variation due to a shift of the feeding and resting times by half a day. Another measure affects the design value of the ventilation system by a higher volume flow rate during summertime. Details on AM are presented below.

Direct evaporative cooling: Cooling pads CP

In confined livestock buildings, direct evaporative cooling devices are in use to convert sensible heat (air temperature) via evaporation of water into latent heat (humidity) with the major goal to reduce the inlet air temperature. We assume cellulose as matrix to increase the wet surface. The efficacy of the CP η_{CP}, also called wet bulb depression efficacy (ASHRAE 2009) is expressed by

$$\eta_{CP} = \frac{T_{out} - T_{CP}}{T_{out} - T_{out,WB}} 100\% \qquad (1)$$

with the outside air temperature (dry bulb) entering the CP T_{out}, the air temperature leaving the CP, entering the livestock building as inlet air T_{CP}, and the wet bulb temperature of the outside air $T_{out,WB}$. For the calculation we assumed η_{CP} = 80%.

Indirect evaporative cooling: Cooling pads combined with a regenerative heat exchanger CPHE

Indirect evaporative cooling systems result in a reduction of the inlet air temperature by evaporation without humidification. The outside air is cooled using direct evaporative cooling. Then this evaporatively cooled secondary air cools the outside air in a conventional air-to-air heat exchanger. We assumed CP and a downstream heat exchanger HE with a constant sensible efficiency of η_{CP} = 80% and η_{HE} = 65% (ASHRAE 2008), respectively, shown in Fig. 1.

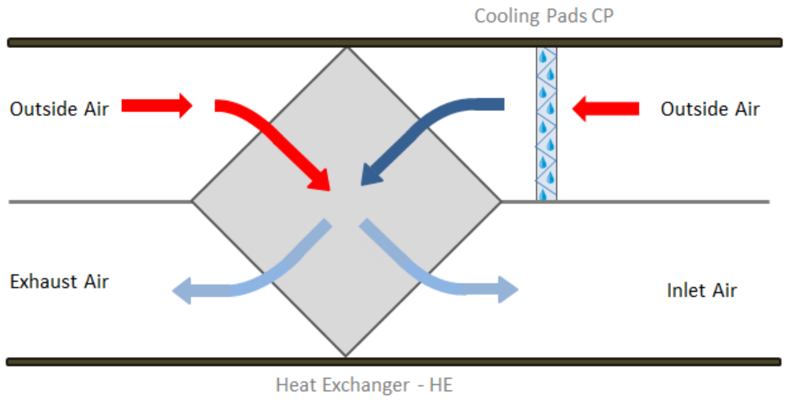

Fig. 1 Schematic diagram of an air treatment by indirect evaporative cooling CPHE: Cooling pads CP combined with a regenerative heat exchanger HE

Earth-air heat exchanger EAHE

EAHEs utilise the ground as an heat storage. Outside air flows through tubes with a diameter D in the range between 0.1 and 1.0 m and a length L between 20 m and 200 m, burrowed in a depth z between 1 and 3 m. EAHEs are well-investigated and practically tested energy-saving air treatment devices. The performance, i.e. air temperature and humidity at the end tubes, depends on the soil temperature T_s, the outside air temperature and humidity, the thermal features of the soil and the geometry of the tubes (Bisoniya et al. 2014; Ozgener 2011; Tzaferis et al. 1992). All calculations were performed with the *number of transfer units* NTU method. The calculation of the model parameter for the sensible and latent heat transfer can be found in detail by Vitt et al. (Vitt et al. 2017).

Reduction of stocking density SD during summer season

To reduce the animal heat release during the warm season the stocking density was reduced. For those fattening periods which are starting between the 57th and the 119th day of the year (about 1st March till 30th April), the SD was reduced. Two scenarios were calculated with a reduction to 80% (SD80%) and 60% (SD60%) compared to REF.

Increase of the summer ventilation rate VENT

To reduce the increase of the indoor temperature due to the sensible heat release of the animals, the maximum ventilation rate was doubled.

Inversion of the diurnal feeding and resting pattern SHIFT

By a shift of the feeding and resting time pattern by about half a day, the maximum of the outdoor temperature coincides with the resting time. The time shift of 10 hours was determined by the diurnal temperature variation of heat days (daily maximum > 30 °C) as shown in Fig. 2.

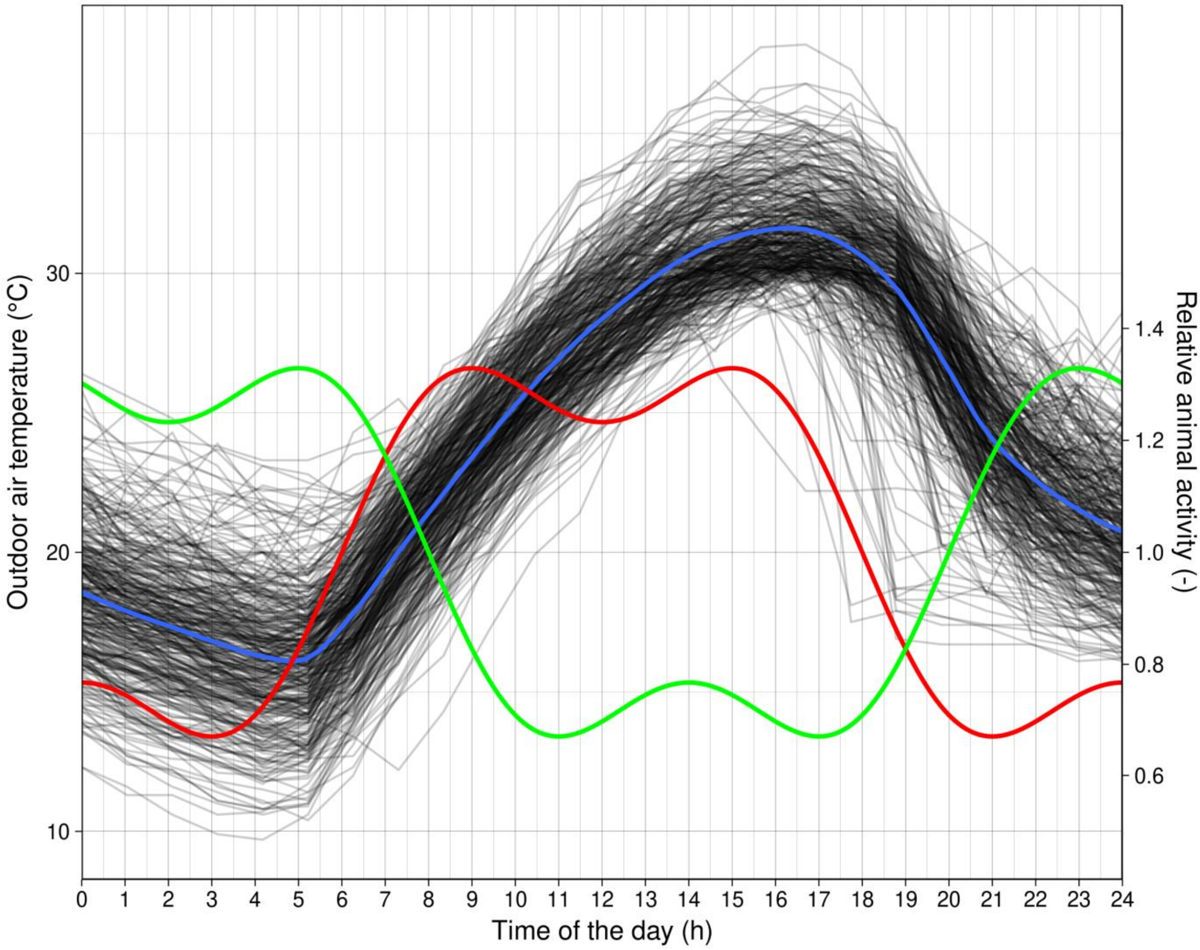

Fig. 2: Diurnal variation of the temperature of heat days (daily maximum > 30°C) between 1981 and 2017 and the time pattern of the relative animal activity for the business as usual reference building REF which describes the feeding and resting time schedule (red line) and the pattern by a shift of 10 hours (green line).

3. Results

This paper focuses on heat stress and related AM. The AM effects (exceedance frequency P_x and area under the curve A_x) are therefore presented for the thresholds of the indoor air temperature $X_T = 25$ °C and the temperature-humidity index $X_{THI} = 75$. The annual maximum for the heat stress parameters could be found for 2003 and 2015, the minimum appears mostly in 1984 but also in some other years (1985, 1990, 1996) (Tab. 3). We selected 2003 as one of the hottest years in the period 1981 to 2017 to present daily maximum values for REF and the seven AM during summer (Fig. 3). The scenarios without air treatment (SHIFT, SD80%, SD60%, and VENT) lie close to REF showing limited effectiveness. The two air treatment scenarios with adiabatic cooling (CP and CPHE) show a better performance. The far best cooling performance was reached by the EAHE.

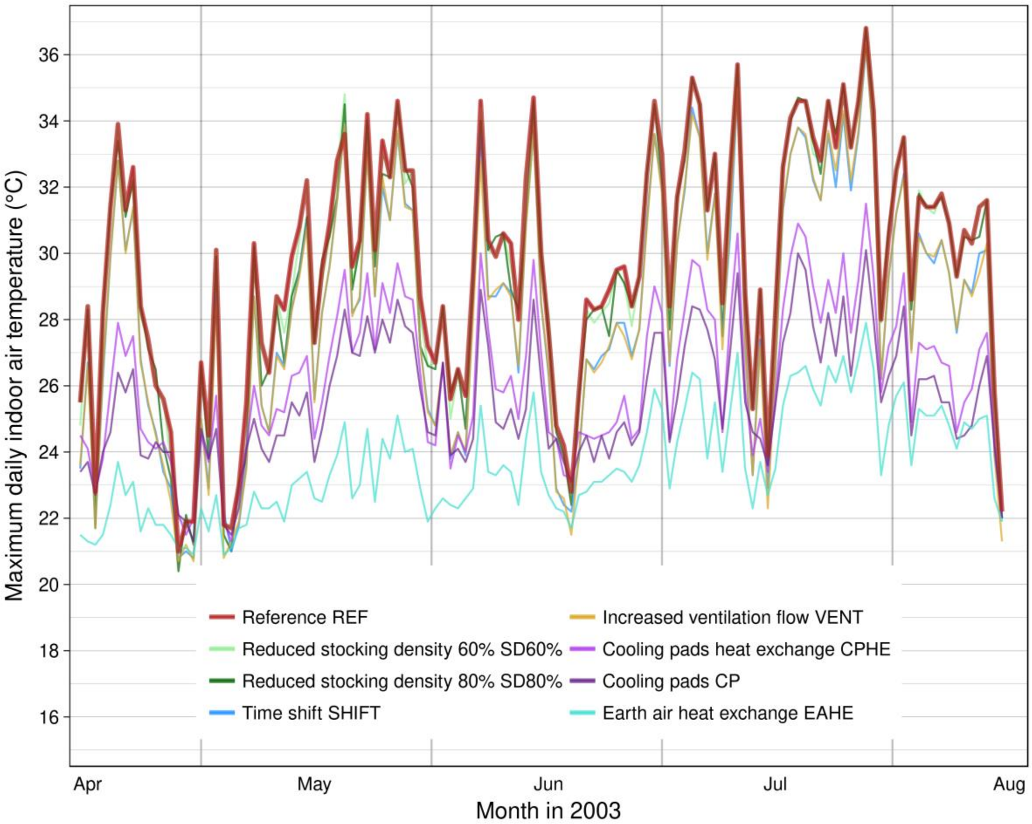

Fig. 3: Daily maximum of the indoor air temperature T for the summer months 2003 for the business as usual reference building REF and the seven adaptation measures AM: (1) cooling pads CP, (2) cooling pads with heat exchanger CPHE, (3) earth-air heat exchanger EAHE, (4) inverted diurnal time pattern SHIFT, (5 & 6) reduced stocking density by 80% (SD80%) and 60% (SD60%) and (7) increased ventilation flow rate VENT

The mean linear trend of the exceedance parameters P_X and A_X is positive for all heat stress measures (exceedance of the threshold values X_T, and X_{THI}), showing a mean relative annual change for the indoor climate of 1.3% (P_T) and 3.0% (P_{THI}) per year for the exceedance frequency P_X and 2.4% (A_T) to 6.4% (A_{THI}) for the exceedance area A_X. This shows that the heat stress is not only caused by the temperature increase but is also due to the increase of the humidity inside the livestock building (Mikovits et al. 2018).

The performances of the seven AM were analysed by the reduction factor R which is related to the heat stress of REF (Tab. 3). The seven AM were ordered ascending according to the reduction factor R, as a measure of the performance. The weakest performance was calculated for the reduction of the stocking density with a reduction factor of R below 10% of most of the heat stress measures. The reduction factors for SHIFT and VENT are between 22% and 51%. The highest heat stress reduction of more than 50% was found for the air treatment devices (CP, CPHE, and EAHE).

The linear slope of the temporal trend k was used to evaluate the resilience of the livestock building against heat stress (Tab. 3). The systems without air treatment (REF, SD60%, SD80% and SHIFT) show a higher slope compared to the outdoor temperature which is identical with the inlet air temperature. This means that the situation inside livestock buildings is worsened compared to the outside situation (Mikovits et al. 2018). For the three air preparation systems the resilience of the livestock system was reinforced not only compared to REF but also to the outdoor situation. By using EAHE the slope diminishes close to zero, which means that even for the ongoing global warming during the last decades the situation inside the livestock buildings remained unchanged.

The time lag TL gives a measure for the gain in time which can be expected on the basis of the reduction factor R and the linear trend k of the heat stress parameters. A $TL = 10$ a means that 10 years after reference year 1981 the expected mean heat stress for a certain AM will be the same as REF in 1981 (Tab. 3). For the two AM varying stocking density, i.e. SD60% and SD80%, the gain in time lies below 7 years which is not a major benefit compared to REF. By SHIFT and VENT a gain in time between 15 and 35 years can be expected, whereas the three air treatment devices (CP, CPHE, and EAHE) lie above 50 years gain in time.

Tab. 3 Statistics of the heat stress parameters by the use of the mean annual linear trend, the calculated reference value for 1981, minimum (Min) and maximum (Max) with years of occurrence between 1981 and 2017, the retardation TL (a) and the reduction factor R (%) of the adaptation measures AM related to the business as usual reference building REF in 1981 of the exceedance frequency P_X and the exceedance area A_X for the threshold of air temperature X_T = 25 °C and temperature humidity index X_{THI} = 75 presented for all adaptation measures: business as usual reference building REF, reduced stocking density SD80% and SD60%, diurnal shift of the activity pattern SHIFT, the increase of the summer ventilation rate VENT, the cooling pads plus heat exchanger CPHE, cooling pads CP, and earth air heat exchanger EAHE. The heat stress metrics for the outdoor situation were added.

Exceedance frequency P	**Trend k**	**1981**	**Min (year)**	**Max (year)**	**TL**	**R**
Temperature P_T for X_T = 25 C						
Outdoor	6.110 ± 1.460	197	92 (1984)	593 (2015)		
Reference REF	7.849 ± 1.847	621	420 (1984)	1139 (2003)	-	-
Stocking density 80% SD80%	7.438 ± 1.813	597	419 (1984)	1107 (2003)	3	4
Stocking density 60% SD60%	7.255 ± 1.783	569	385 (1984)	1073 (2003)	7	8
Diurnal shift SHIFT	8.746 ± 2.052	440	256 (1984)	1005 (2003)	21	23
Ventilation rate VENT	6.599 ± 1.644	389	221 (1984)	843 (2003)	35	34
Cooling pads plus heat exchanger CPHE	7.320 ± 1.470	176	99 (1984)	617 (2003)	61	61
Cooling pads CP	6.235 ± 1.300	97	34 (1990)	479 (2003)	84	74
Earth air heat exchanger EAHE	1.473 ± 0.634	28	1 (1996)	220 (2015)	403	93
Temperature humidity index P_{THI} for X_{THI} = 75						
Outdoor	4.372 ± 0.991	35	12 (1997)	347 (2015)		
Reference REF	7.462 ± 1.619	248	132 (1984)	715 (2003)	-	-
Stocking density 80% SD80%	7.277 ± 1.547	232	124 (1984)	678 (2003)	2	5
Stocking density 60% SD60%	6.867 ± 1.530	224	115 (1984)	666 (2003)	3	9
Diurnal shift SHIFT	7.372 ± 1.619	134	68 (1984)	616 (2015)	15	33
Ventilation rate VENT	6.261 ± 1.272	113	57 (1984)	476 (2003)	22	43
Cooling pads plus heat exchanger CPHE	4.159 ± 0.926	41	1 (1990)	299 (2003)	50	72
Cooling pads CP	2.842 ± 0.737	24	1 (1996)	227 (2003)	79	82
Earth air heat exchanger EAHE	0.493 ± 0.159	0	0 (1985)	50 (2013)	505	98

Exceedance area A						
Temperature A_T for X_T = 25 C						
Outdoor	23.24 ± 6.51	387	202 (1984)	2516 (2015)		
Reference REF	40.45 ± 9.85	1703	952 (1984)	4461 (2015)	-	-
Stocking density 80% SD80%	39.09 ± 9.66	1605	922 (1984)	4398 (2015)	3	5
Stocking density 60% SD60%	36.72 ± 9.60	1537	868 (1984)	4155 (2015)	5	10
Diurnal shift SHIFT	36.45 ± 9.45	999	530 (1984)	3936 (2015)	19	34
Ventilation rate VENT	31.73 ± 8.06	917	462 (1984)	3325 (2015)	25	40
Cooling pads plus heat exchanger CPHE	16.02 ± 3.48	202	96 (1990)	1208 (2015)	94	81
Cooling pads CP	10.10 ± 2.28	86	16 (1990)	715 (2015)	160	90
Earth air heat exchanger EAHE	1.54 ± 0.77	12.6	0 (1996)	274 (2015)	1101	99
Temperature humidity index A_{THI} for X_{THI} = 75						
Outdoor	11.550 ± 3.131	44	7 (1990)	1077 (2015)		
Reference REF	30.430 ± 6.555	479	294 (1984)	2463 (2015)	-	-
Stocking density 80% SD80%	29.480 ± 6.354	439	277 (1984)	2431 (2015)	1	6
Stocking density 60% SD60%	27.150 ± 6.280	429	272 (1984)	2285 (2015)	2	11
Diurnal shift SHIFT	22.810 ± 5.504	212	115 (1989)	2003 (2015)	12	44
Ventilation rate VENT	20.550 ± 4.691	181	99 (1990)	1681 (2015)	15	51
Cooling pads plus heat exchanger CPHE	6.959 ± 1.810	44	1 (1990)	552 (2013)	63	86
Cooling pads CP	3.863 ± 1.215	26	0 (1996)	377 (2013)	117	92
Earth air heat exchanger EAHE	0.364 ± 0.162	-0.4	0 (1985)	46 (2011)	1317	100

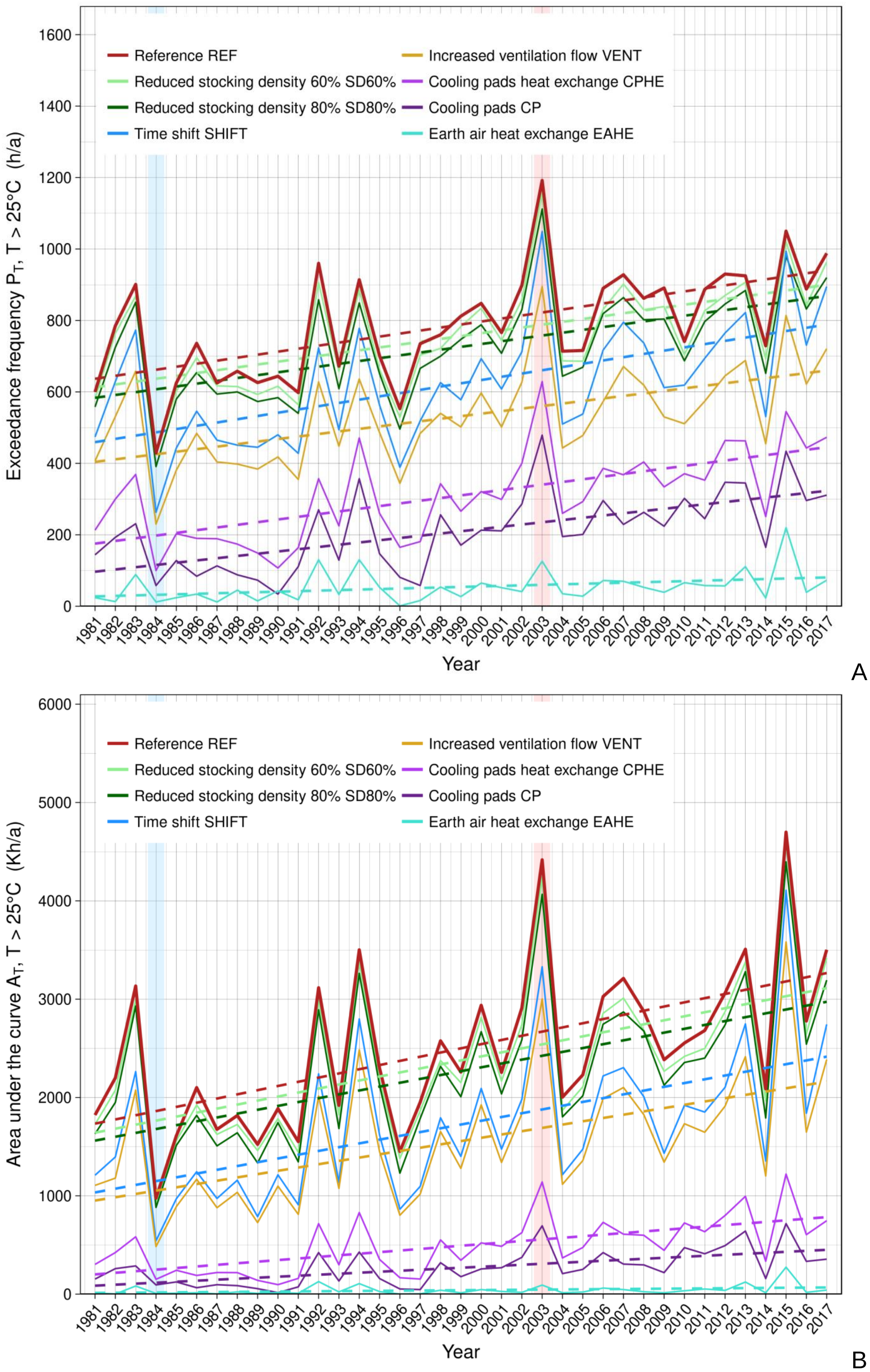

Fig. 4: Annual exceedance frequency P_T (A) and exceedance area A_T (B) for the threshold of the indoor air temperature X_T = 25 °C determined for the business as usual reference system REF and the seven adaptation measures AM: reduced stocking density SD80% and SD60%, diurnal shift of the activity pattern SHIFT, the increase of the summer ventilation rate VENT, the cooling pads plus heat exchanger CPHE, cooling pads CP, and Earth air heat exchanger EAHE. The linear regressions are shown by dashed lines.

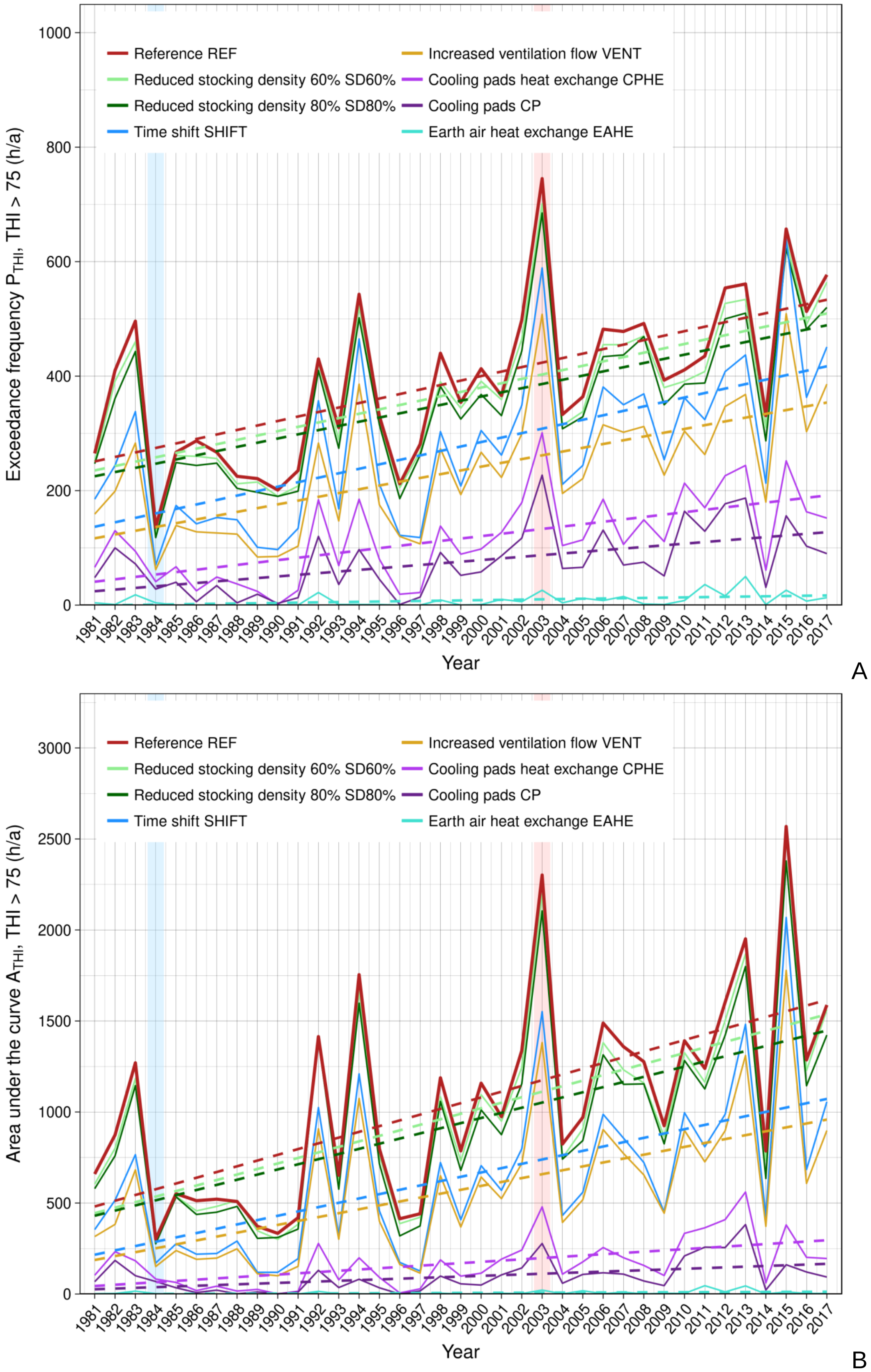

Fig. 5: Annual exceedance frequency P_T (A) and exceedance area A_T (B) for the threshold of the temperature humidity index X_{THI} = 75 determined for the business as usual reference system REF and the seven adaptation measures AM: reduced stocking density SD80% and SD60%, diurnal shift of the activity pattern SHIFT, the increase of the summer ventilation rate VENT, the cooling pads plus heat exchanger CPHE, cooling pads CP, and Earth air heat exchanger EAHE. The linear regressions are shown by dashed lines.

4. Discussion

The model calculations of a confined livestock building for fattening-growing pigs typical to industrial systems show that heat stress is a major concern for the well-being, the health, and the performance of the animals. This effect is not only caused by the variability of the meteorological parameters but also be a distinct temporal trend caused by climate change. For 1981 to 2017 the pig related heat stress parameters show a relative increase of 0.9% (P_{TU}) to 3.0% (P_{THI}) per year for the exceedance frequency P_X and 1.5% (A_{TU}) to 6.4% (A_{THI}) for the exceedance area A_X (Mikovits et al. 2018). It could be shown, that the resilience of the indoor climate of the reference system without AM is distinctly lower compared to the meteorological values outdoor. This shows the necessity of simulation models for the thermal indoor climate of confined livestock buildings.

Therefor the performance of several AM to reduce or avoid thermal stress were investigated. The performance of these AM were evaluated by the reduction factor and the time gain which helps to overcome the growing load of heat stress in the future. The model calculations reveal two groups of AM. AM of the first group are more related to livestock management and can be easily introduced on a farm. Even if the reduction of the stocking density doesn't need investments and reduces variable costs, the opportunity costs of forgone revenues can be high.

The second group are energy saving air preparation systems which need investments and will provoke additional operating costs as well (Vitt et al. 2017). The three air treatment devices CP, CPHE, and EAHE are compatible with current livestock housing systems. They can be seen as incremental AM to avoid disruptions of the current livestock systems in the future (Kates et al. 2012). The results of the air preparation devices show that the EAHE is the most efficient air treatment device. It eliminates heat stress depending on the selected heat stress parameter between 90% and 100% and can also be used during wintertime to increase the inlet air temperature. This will increase the air quality as well. CP will reduce heat stress by 74% to 92% with the disadvantage that the inlet air will be moistened. CPHE can avoid this shortcoming at the expense of a limited heat stress reduction between 61% and 86% and higher investment costs. Nevertheless, the profitability of both management-based AM and these air preparation AM has to be investigated.

The advantages of the presented model approach in comparison to measurements are manifold: (1) the model can be applied to other sites by the use of corresponding meteorological datasets, (2) near future scenarios can be assessed by the extrapolation of the linear trend of long time series (e.g. 1981 to 2010), (3) future climate scenarios can be calculated by datasets on an hourly basis (e.g.van Leuken et al. 2016), (4) case studies can be performed for combinations of AM to optimise the indoor climate by the use of heat stress parameters as a cost function, and (5) future developments of system parameters can be considered (e.g. market demand of heavier pigs at slaughter).

The model calculations were performed for a site in Austria located in Central Europe. The climate is within class Cfb (temperate oceanic climate) of the Köppen-Geiger climate classification which is representative for large areas in Central Europe excluding the Alps. The pig density (Robinson et al. 2011; Robinson et al. 2014) and farm density (Marquer 2010) shows the highest values for this climate class Cfb as well. This agreement between climate class Cfb and animal density can be found for North America and Asia (predominantly China) too. Therefor the evaluation of the AM performed for a site in Austria can be used as an educated guess for most areas where pork production is performed in industrial systems with confined livestock buildings.

Currently about 50% of world's pork production and 70% poultry meat production originates from industrial systems (Steinfeld et al. 2006), in future pig stocks in intensified systems are estimated to increase 3.0 to 3.5 times, broilers 4.4 to 5 times, and layers 2 to 2.4 times (Fischer et al. 2006). In respect to the environmental impact of livestock the industrial systems have the advantage that they show a lower CO_2 footprint per unit of product (e.g. due to an increase of the feed conversion ratio) (Audsley et al. 2010), a better management of other pollutants (ammonia and odorous substances) (Schauberger et al. 2018), and a greater efficiency in energy demand for industrial systems (broiler chickens (4.5) and pigs (9.3)) compared to beef cattle (13.3 to 40 depending on diet and age)) (Misztal 2017). Past structural developments and investments in the livestock industry indicate the larger economic profitability of industrial systems and powerful economies of scale as well. This shows the increasing demand for investigations in the field of confined livestock buildings especially by the fact that most of the literature is exploring climate impacts on grassing animals and not on livestock in such industrial systems (Weindl et al. 2015). Furthermore, concerns about animal welfare appear a priority to the society in recent years.

The advantage of the presented model approach is the quantification of heat stress in comparison to qualitative assessments (e.g. Derner et al. 2017).

All AM can be divided in relation to their costs, complexity, knowledge requirements of the farmers, and the time scale (Holzkämper 2017). AM related to management can be applied on the short term such as SD60% and SD80% and SHIFT. They can be seen as incremental responses, often chosen autonomously by the farmers in response to observed changes and based on local knowledge and experience. These management measures can be applied on a short-term basis from year to year and need only limited investments. The second group are long-term adaptations with a transformative response that require strategic planning. Planning for new livestock buildings should foresee options for potential AM implementation at least. Therefore the data for the design and planning of AM have to be known early enough for farmers, consultants, and veterinarians to ensure a high level of sustainability in livestock production (Walker et al. 2013). In this context air treatment devices are long-term structural measures and investments. The lead time and the lifetime of these measures determine their economic profitability (Dittrich et al. 2017).

5. Conclusions

Global warming negatively impacted livestock keeping in confined buildings during the last three decades will do so in the future according to the trend analysis in this study. Robust measures of heat stress inside the livestock buildings can only be quantified by a simulation model of the indoor climate over longer time periods. Compared to the outdoor raised farm animals, the indoor situation shows a lower resilience. By the use of adaptation measures heat stress can be reduced and resilience increased. Especially energy saving air preparation devices can reduce heat stress in the range between 60 and 100%. Other adaptation measures like the reduction of the stocking density and the shift of the activity pattern of the animals to night-time are less effective.

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Conflict of Interest

The authors declare that there is no conflict of interest

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