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Review

Efficacy of adaptation measures to alleviate heat stress in confined livestock buildings in temperate climate zones[‡]

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Global warming has caused an increase in frequency and degree of heat stress over the last decades. In conventional livestock husbandry systems with insulated buildings, mechanical ventilation systems and high stocking density pigs and poultry can be more affected by climate change than in free range husbandry systems. To reduce heat stress in livestock buildings, adaptation measures are used. This article assesses a wide variety of adaptation 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), modification of the indoor climate at the animal level (e.g., fogging, cooling the drinking water, increasing air velocity), and adaptation of livestock management (e.g., reduction of stocking density). The efficacy of some of these measures was quantified using simulation models and then used as a benchmark for assessing the efficacy of other measures. The efficacy of the various adaptation measures varies widely: air treatment devices which are cooling the inlet air showed the highest performance, while measures aimed at reducing the heat release of the animals (e.g., lower animal density, higher ventilation rate) performed poorest. In confined livestock systems, the reduction of heat stress by implementing adaptation measures will reduce economical losses. The selection of appropriate adaptation measures, in addition to

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improving animal welfare, can also be seen as a contribution to strengthen the economic resilience of farmers.

Nomenclature

U (W m^{-2} K^{-1})	thermal transmittances of building elements
SD (%)	stocking density
THI (–)	temperature humidity index
P (h a^{-1})	exceedance frequency
A (Kh or h)	Area under the curve
T (°C)	air temperature
η_{CP} (%)	wet-bulb depression efficacy
AM	adaptation measure
BREED	adapted breeds
CONDUCT	cooled laying area
Cfb	Köppen-Geiger climate classification class (warm temperature, fully humid, warm summers)
CP	cooling pads
CPHE	Cooling pads and heat exchanger
EAHE	earth-air heat exchanger
FEED	feeding strategies
FOGGING	fogging
FORCED	increased air velocity
GEO	geothermal cooling by groundwater
INSULATION	insulation of the buildings
ORIENTATION	building: orientation of the building
RADIANT	radiative cooling
REF	reference system REF
ROOF	green façade/roof sprinkling
SHADE	shading by plants
SHIFT	shift of the resting and activity periods
SPRINKLING	sprinkling
VENT	doubling the ventilation rate
WALLOW	wallow
WATER	chilled drinking water

1. Introduction

Livestock farming is directly and indirectly impacted by global warming. Extensive farming systems are directly impacted by heat stress, while higher consumption of water and energy for cooling measures means indirect impact for all husbandry systems. The majority of pigs and poultry in mid-latitudes are kept in confined livestock buildings (Robinson et al., 2011); at global level, this accounts for more than half of the systems (Niamir-Fuller, 2016). Such systems are predominantly located in similar temperate climates with a strong accumulation in the Cfb group, according to Köppen-Geiger climate classification, i.e. temperate oceanic climate (warm temperature, fully humid, warm summers). This coincidence between the climate group Cfb and animal density (Robinson et al., 2011, 2014) can be found for Europe, North America and parts of Asia (predominantly China). In the respective regions, pigs and poultry are predominantly kept in so-called industrial systems (Gerber et al., 2013), which are characterised by well-insulated buildings, mechanical ventilation systems, and high stocking densities.

Compared to crop production, relatively few studies are available concerning the impact of climate change on livestock. In their systematic literature review, Escarcha et al. (2018) pointed out that only 14% of the publications they examined considered intensive livestock production, only 19% considered monogastric animals (poultry and pigs), and only 6% dealt with the quantification of climate change impacts and the adaptation of livestock husbandry. A reason for this lack of data could be that ruminants are an important source of methane (greenhouse gas), and pasture and grassland keeping of animals can be evaluated solely by meteorological parameters without elaborated modelling of the indoor climate of livestock buildings. Due to the lack of quantitative studies on livestock buildings, it is difficult for livestock managers or public administrators to select system configurations that will allow the prediction of challenges caused by global warming. Lacking data may also aggravate research funding decisions towards improved intensive livestock systems.

Skuce et al. (2013) summarised the adaptation options in confined livestock systems that can reduce heat stress caused by global warming as follows: (1) improved mechanical ventilation systems/regimes; (2) additional cooling/heating systems; (3) changes in stocking density; (4) slower growing pigs/birds (to reduce thermal loads and incidence of growth-associated pathologies); (5) more heat tolerant lines/strains (genetic selection/genomic strategies); and (6) nutritional measures. According to these requirements, we analyse here adaptation measures (AMs) for confined livestock systems in temperate regions with special emphasis on their efficacy to reduce heat stress (Le Bellego et al., 2002; Lin et al., 2006; Mikovits et al., 2019; Renaudeau et al., 2012). By implementing such AMs, confined livestock production systems may be able to cope with future climate conditions in the next few decades (Rust, 2019).

In contrast to many other investigations, the focus of this work is not on the evaluation of cooling performance of a single adaptation method but comparing all selected AMs concerning their efficacy.

The analysed AMs were grouped into those effective at the housing level and measures those that affect individual animals. In the first group, AMs were assessed according to their impact on the indoor climate of the confined livestock building, as characterised by the thermal environment and air quality. The assessment at housing level has the advantage that these AMs can be included in simulation models based on meteorological data (Mikovits et al., 2019). Such a model approach can be evaluated for all geographical regions for which meteorological data are available. Furthermore, two or more AMs can be combined to form an optimum solution for a climatic situation and the specific livestock building. AMs aimed only at the animal level cannot employ such a modelling approach.

Firstly, the AMs investigated are described and discussed. Secondly, the efficacy of the AMs are evaluated on the basis of their heat stress reduction capacity. The efficacy of seven AMs, where model calculations are available, are taken as benchmarks for this evaluation (Schauberger et al., 2019).

2. Adaptation measures

AMs are grouped into (1) systems which are part of the ventilation system and modify the thermodynamic properties of the inlet air (air temperature and humidity) (2) elements which are part of the building (e.g., insulation), or features of the building (e.g., orientation), (3) indoor equipment on the animal level, which modifies the indoor climate on a small scale, and (4) adaptation of the livestock itself and its management.

2.1. *Air treatment devices for the ventilation system*

Due to their high animal density, confined livestock buildings are usually equipped with mechanical ventilation systems fulfilling two major functions: (1) providing sufficient air quality during winter in combination with an inside air temperature close to the thermo-neutral zone of the animals, and (2) minimising the difference between indoor and outdoor temperature by using high ventilation rates to avoid sensible heat accumulation in the building during summer. Many farms in Austria, and elsewhere, do not use any air treatment system which means that outside air is transported without any modification into the building as inlet air. Exceptions are heating periods for specific age-groups (especially young animals, e.g. broilers during the beginning of the growing period and piglets), which need a high indoor temperature.

Air treatment devices modify the thermodynamic properties of the inlet air. In principle, there are little technical constraints to guarantee a certain indoor climate, as expressed by temperature and humidity. Limitations result from economic constraints due to high investment, energy, and maintenance costs. Therefore only systems which do not need energy for cooling and/or dehumidification were selected, whereas supplemental energy for pumping or to overcome additional flow resistance by fans is often needed. Systems included are: (1) earth-air heat exchanger EAHE (Bisoniya et al., 2014; Tzaferis et al., 1992), (2) direct evaporative cooling devices i.e. cooling pads CP (Renaudeau et al., 2012; Valiño et al., 2010; Xuan et al., 2012), (3) indirect evaporative cooling systems which combine evaporative cooling (e.g. by cooling pads) with a subsequent heat recovery system CPHE (Heidarinejad et al., 2009; Sax et al., 2012; Struck et al., 2014; van Caenegem et al., 2012), and (4) geothermal cooling of the inlet air by a heat exchanger using groundwater (Zaidan et al., 2019).

2.1.1. *Earth-air heat exchanger EAHE*

EAHEs utilise earth as heat storage. Outside air flows through tubes with diameters in the range 0.1–1.0 m and lengths between 20 m and 200 m, buried in depths between 1 and 3 m. EAHEs are well-investigated and practically tested energy-saving air treatment devices. Their performance, i.e. air temperature and humidity at the end of the tubes, depends on soil temperature, outside air temperature and humidity, thermal features of the soil and the geometry of the tubes (Bisoniya et al., 2014; Ozgener, 2011; Tzaferis et al., 1992). Besides sensible heat modification due to the EAHE, condensation can take place inside the tubes (Cucumo et al., 2008) if the outside humidity, described as mixing (humidity) ratio (ASHRAE, 2009b), is higher than the mixing ratio in saturated conditions at the end of the tubes. A discussion about the modelling of the efficacy of EAHE can be found in Vitt et al. (2017).

In Fig. 1, a comparison between the inlet air temperature without air treatment (Fig. 1a) and with EAHE (Fig. 1b) is shown (Vitt et al., 2017). Air coming from outside with a temperature

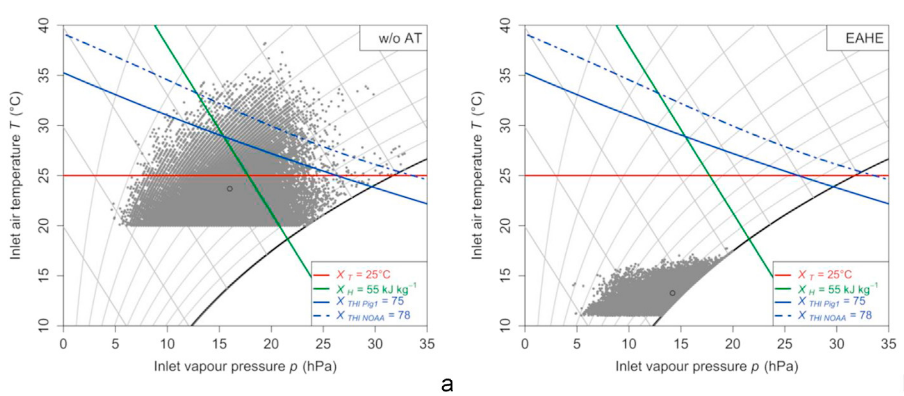

Fig. 1 – Air temperature and vapour pressure of the inlet air for summer conditions (T_{out} > 20 °C). (a) without air treatment w/o AT and (b) earth-air heat exchanger EAHE. For the evaluation of the inlet air, four thresholds of heat stress parameters are shown (temperature X_T = 25 °C, specific enthalpy X_H = 55 kJ kg^{-1}, temperature humidity index THI for pigs $X_{THI\ Pig1}$ = 75, and temperature-humidity index for poultry $X_{THI\ NOAA}$ = 78). The mean value of the inlet air temperature *T* and the inlet vapour pressure *p* is tagged by an open circle (Vitt et al., 2017).

above 20 °C is cooled to a temperature not likely to cause heat stress. In most cases, inlet relative humidity this is >40%.

EAHE have been used since the 1960s (Ozgener, 2011; Scott, 1965). In particular, as a consequence of the energy crisis in the 1970s, several EAHE systems were installed for livestock buildings (Deglin et al., 1999; Krommweh et al., 2014; Müller et al., 2005; MWPS-32, 1990; Schauberger et al., 1980; Schauberger & Keck, 1984). A major advantage of the EAHE is its applicability over the entire year with the following features: (1) effective damping of short-term temperature fluctuations (Hollmuller, 2003), (2) heating of the inlet air temperature during winter which increases the ventilation flow rate and the related indoor air quality, and (3) cooling during summer (Bisoniya, 2015; Hessel & van den Weghe, 2011; van Caenegem & Deglin, 1997; Venzlaff & Müller, 2008). In addition to earth tubes, air-flowed gravel bed systems have also used, which show a similar performance (Krommweh et al., 2014; Reichel, 2017).

2.1.2. *Cooling pads CPs*

In confined livestock buildings, direct evaporative cooling systems have been used to convert sensible heat (temperature) via evaporation of water into latent heat (humidity) with the major goal to reduce the inlet air temperature. A simple realisation are CPs consisting of various matrices, mainly cellulose, plastic, bricks, and metal. Higher efficacy has been shown for cellulose materials compared to plastic (Ahmed et al., 2011; Czarick & Fairchild, 2012).

The efficacy of the evaporative cooling capacity of CPs is described by the so-called wet-bulb depression efficacy (η_{CP}) (ASHRAE, 2009a). Huhnke et al. (2004) and Fehr et al. (1983) assumed a constant efficacy of 70% and 80%, respectively, to mimic the performance of cooling pads. Nääs (2006) reported a range between 52% and 90% for efficacy. Koca et al. (1991) demonstrated that the efficacy is strongly influenced by the geometry of the airflow inside the pads with variations of about ±10%. The advantages and disadvantages of evaporative cooling were summarised in DEFRA (2005).

The impact of CPs as a direct adiabatic cooling system on the inlet air is shown in Fig. 3c in comparison to an inlet air temperature without air treatment shown in Fig. 3a. For an Austrian case study, the efficacy of CPs was in the range of 74 and 90% (Schauberger et al., 2019). Lucas et al. (2000) estimated that for the climate of Portugal the use of cooling pads with an efficacy of 70% can prevent from heat stress during most periods. For China, the applicability of cooling pads was evaluated for different climatic zones using the wet-bulb temperature (Xuan et al., 2012). Results showed that the cooling pads are effective below a wet-bulb temperature of 28 °C. For Central Europe, this requirement is fulfilled as shown in Fig. 3a.

Proper maintenance of CPs is critical for their performance. Concerning service life and maintenance costs, the water quality (salinity and hardiness) and clogging by algae and sludge can be relevant (Al-Helal, 2003; Campbell et al., 2006; MWPS-34, 1990; Stinn & Xin, 2014).

Apart from fogging inside the livestock building (section 2.3), CPs are one of the most widely applied direct evaporative cooling devices. The main advantages of CPs compared to fogging are: (1) if the design, operation, and maintenance are properly carried CPs only affect the condition of the inlet air and neither animals nor litter and (2) CPs clean the inlet air by retaining dust that is continuously removed with the excess water (Nääs, 2006). Panagakis and Axaopoulos (2006) showed, that CPs were the most effective AMs compared to fogging, because they resulted in lower daily inside dry–bulb temperature variation, maximum reduction in the apparent heat stress intensity, and lower total consumption of water.

2.1.3. *Indirect evaporative cooling systems*

Indirect evaporative cooling systems are a combination of evaporative cooling (e.g., by cooling pads) followed by a heat exchanger CPHE (De Antonellis et al., 2016, 2017; Duan et al., 2012; Heidarinejad et al., 2009; Watt, 2012). Such systems have also been suggested for confined livestock buildings (van Caenegem et al., 2012) (Fig. 2).

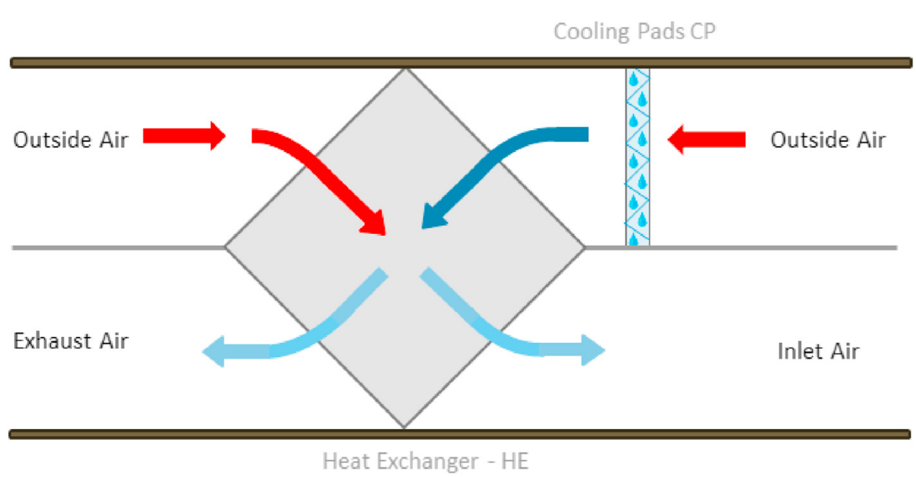

Fig. 2 – Schematic diagram of an air treatment by indirect evaporative cooling using cooling pads combined with a regenerative heat exchanger CPHE. The outside air is cooled and moistened by cooling pads (dark blue arrow), then this air is used to cool outside air without transport of water vapour, and used as inlet air (Schauberger et al., 2019).

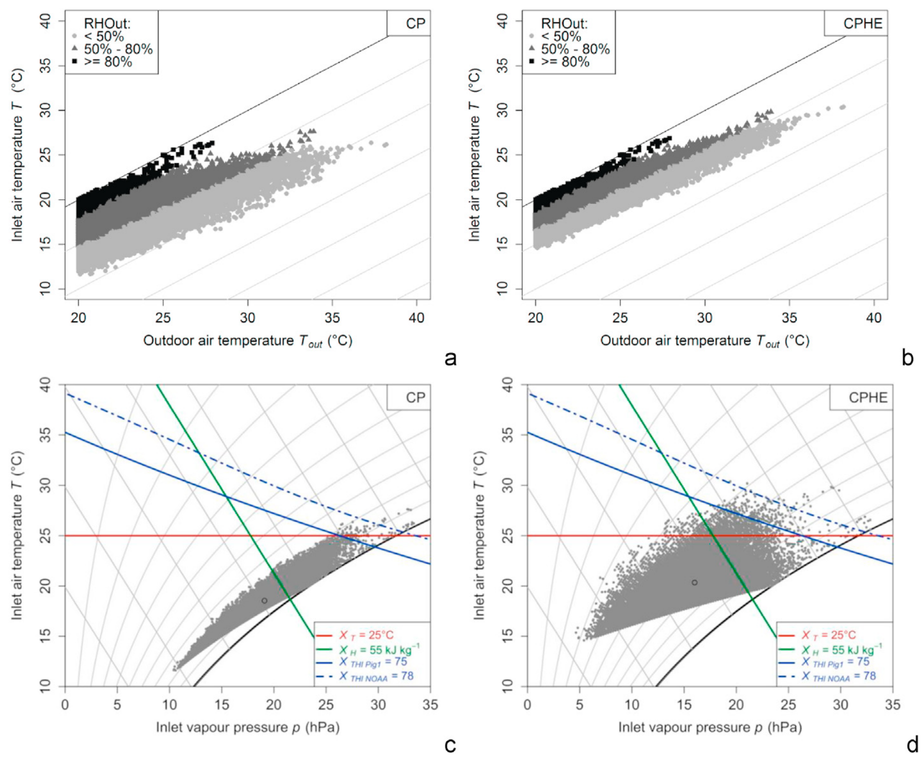

Fig. 3 – Comparison of the performance of CPs and CPHE. Upper panel (a and b): Inlet air temperature as a function of the outdoor air temperature for a low (rH_{out} < 50%), medium (50% ≤ rH_{out} < 80%) and high (rH_{out} > 80%) relative humidity rH_{out} for CPs (left, a and c) and CPHE (right, b and d). The grey lines show the temperature depression of the inlet air by steps of 5 K for summer conditions (T_{out} >20 °C). Lower panel (c and d): Mollier diagram (air temperature and vapour pressure after air treatment for summer conditions (T_{out} > 20 °C) for CPs (left, a and c) and a CPHE (right, b and d) (Vitt et al., 2017).

In agricultural engineering, these systems are widely used to improve the storing conditions of fruits and vegetables (lal Basediya et al., 2013), but no field reports are available for their use in livestock buildings. A detailed description of the modelling and measurements of indirect cooling systems can be found in Boukhanouf et al. (2017) and Hasan (2012). In the context of animal husbandry, the term indirect adiabatic cooling is sometimes misleadingly used for direct cooling inside the building by fogging and sprinkling systems, cooling the animals by wetting the skin, and indirect cooling is restricted to cooling of the inlet air (Hahn, 1981; Hoff, 2013).

The overall efficacy of CPHE depends on the efficacy of both components, (1) the cooling pads in the range between 50 and 90% (ASHRAE, 2009a; Nääs, 2006; Fehr et al., 1983; Huhnke et al., 2004) and (2) the heat exchanger with $\eta_{HE} \approx 80\%$ (ASHRAE, 2008). Other heat exchanger systems, such as rotary energy exchangers (heat wheels) or heat pipe exchangers, are described in detail in ASHRAE (2008). These systems are also recommended for livestock buildings (MWPS-34, 1990). Such heat exchanger devices cannot only be used during summer to reduce heat stress (in combination with cooling pads) but also during winter to increase the inlet air temperature. For the latter, the ventilation rate can be increased (MWPS-34, 1990) which will substantially improve the indoor air quality.

The use of CPs and CPHE can also increase biosecurity by reducing dust and bioaerosols. Reported drawbacks are a higher probability for the occurrence of mosquito breeding hotspots, legionella bacteria and other microorganisms due to poor maintenance of these systems. This might be an important safety aspect for workers inside the livestock buildings and also a risk factor for animal health (Samuel et al., 2013).

The differences between CP and CPHE cooling efficacy are shown in Fig. 3 with the cooling performance of CPs (Fig. 3a) depending in part on the outside relative humidity. The grey lines, parallel to the line of identity, indicate the observed temperature depression. For CPs, the reduction of air temperature is distinctly higher, compared to the CPHE. The additional moistening of the inlet air is shown by the combination of the inlet air temperature and inlet humidity (Fig. 3c and d). Due to the concept of CPHE, the vapour pressure of the inlet air is the same as for the outside air. In contrast to that, the use of CPs increases the inlet air humidity.

2.1.4. *Geothermal cooling by the use of groundwater*

Using finned coil heat exchangers, groundwater can be used to cool the inlet air. Depending on the depth of the abstraction, the groundwater temperature lies within the range of the annual mean air temperatures (Samuel et al., 2013). Jacobson (2012) showed the applicability for livestock buildings and the economic benefit in the Midwest USA. By cooling during summertime, the maximum ventilation rate can be reduced from about 240 m^3 h^{-1} per sow to 70 m^3 h^{-1}, which will decrease the electrical energy demand on the farm. Compared to evaporative cooling devices such as CPs, the cooling of the inlet air is maintained without any increase in humidity. Facilities can combine cooling of the inlet air and floor of the laying area. A limitation for this heat source (in winter) and heat sink (in summer) is the availability of groundwater.

2.2. Impact of building characteristics

The impact of building characteristics on the indoor climate is determined by the thermal properties of the roofs and walls. The impact of the outside conditions is determined by wind velocity, prevailing wind direction and the solar radiation on roof and walls. This means that the geographical orientation of the building influences the impact of outside conditions and has to be taken into account during the assessment of the effectiveness of AMs. During winter, the U value (referred to as heat transfer coefficient or thermal transmittance) is the relevant parameter which describes the sensible heat flow depending on the surface area and the difference between indoor and outdoor air temperature. For warm livestock buildings, this temperature difference ΔT can reach up to 30–40 K during wintertime. During summer, the ventilation flow rate is about 8–10 times higher than during wintertime. This implies a high coupling between the outdoor and the indoor situation so that the impact of the thermal features of the building on the indoor climate is limited because the temperature difference lies in the range of only 3–5 K between indoor and outdoor.

During summertime, the impact of solar irradiance on the surface areas of the livestock building is more important. This causes a strong influence of the orientation of the building on the heat flow caused by solar radiation (Axaopoulos et al., 2014). Angrecka and Herbut (2016) found that a longitudinal E–W axis is the optimal orientation of a livestock building because direct entry of solar radiation into the building is reduced due to the increased extension of the surface towards North.

The third meteorological predictor is the wind velocity, which increases the convective heat transfer on the outside surface area of the building. Planting of green vegetation in front of the walls, where solar radiation heats the surface, can reduce this additional heat flux (Angrecka & Herbut, 2016). Depending on the density of plants, a reduction of the wind velocity close to the wall surfaces can reduce the convective heat transfer and the resulting thermal transmittances (U value) which is beneficial during winter. For buildings with additional insulation, the orientation shows no impact on the indoor climate (Axaopoulos et al., 2014). This implies, that the positive impact of wind convective cooling can be neglected so that planting will be beneficial to reduce the load by solar radiation.

Features of the roof for the reduction of the heat load inside the building are (1) a white painting or cover to increase the reflectivity, (2) green roofs, covered with vegetation, allowing evaporative cooling over the entire diurnal cycle, and (3) irrigation of roofs (La Roche & Berardi, 2014; Yeom & La Roche, 2017). A major disadvantage of green roofs is the additional maintenance costs and construction costs due to higher roof loads. Levinson and Akbari (2010) assessed the impact of white roofs (solar reflectance about 0.55) versus grey roofs (reflectance ~ 0.20, a typical value for conventional roofs) for buildings occupied by humans in the US, which depended on the thermal properties of the buildings, characterised by the U value. To achieve a long-lasting effect of roof sprinkler systems, they should be covered with water-absorptive and retentive materials such as sandbags and brick ballast, which behave like a free water surface for evaporation (Lokapure & Joshi, 2012).

The better the insulation (low U value), the lower the effect of building orientation and roof cooling methods, which also has impact on the economic payback of such measures (Czoske & Neusch, 2012). For buildings with low insulation for the walls and especially the roof (e.g., a "tin" roof), the inside surface temperature due to solar radiation will be much higher. This high surface temperature will reduce the sensible heat release of the animals by longwave radiation. This effect is not covered by the common heat stress parameters used for the assessment of the indoor climate, because it does not include the mean radiation temperature (Brooke Anderson et al., 2013).

During summer, the heat load by solar radiation coming through the windows, or shading) has to be taken into account. For a solar irradiance of about 1000 Wm^{-2} at noon, an additional sensible heat load of up to 30 W m^{-2} can be assumed if the window area is about 3% of the area of the ground floor. This additional heat load cannot be neglected for the sensible heat balance of the livestock building. The impact of solar radiation can be reduced by green vegetation but it needs to be tall enough to shade the windows and may also alter indoor light conditions. Differing national regulations for illuminance inside livestock buildings by solar radiation or artificial light (e.g. Austria 40 lux, Germany 80 lux) must be taken into account.

2.3. Adaptation measures (AMs) on the animal level

The previously discussed AMs had impacts at the housing level, which means that the entire livestock building is influenced by these measures due to modifications of the inlet air or the heat load passing the building shell. On a smaller scale, several AMs can affect the local environment of the individual animal, by modifying the conductive, evaporative, radiative, and convective heat release mechanisms of the animals, in combination or alone.

2.3.1. Forced air velocity

Forced ventilated livestock buildings (e.g. boost, circulation fans), or hybrid ventilation systems, which can be used in a naturally ventilated livestock buildings by the use of additional fans. The air velocity close to the animal surface can be increased to raise the convective heat release. These additional fans do not impact the ventilation rate because they only increase the local indoor air velocity in the recirculation mode. However, there is a high risk that these circulation fans provide an uneven distribution of the air velocity inside the livestock building, which can therefore exceed critical values and cause air draughts. As a consequence, animals can crowd in those parts of the livestock building, where they are not disturbed by air draughts. Critical values are <0.2 m s^{-1} in winter and >1.5 to >2.5 m s^{-1} for poultry and >0.6 m s^{-1} for pigs in summer. Air draught is considered to be one major risk factor for the outbreak of tail biting in pigs (Schrøder-Petersen & Simonsen, 2001). If animals remain stationary and are not able to avoid areas with air draught, this constitutes a severe welfare issue. To avoid stresses caused by air draught, more sophisticated systems based on air duct and air inlets are used to improve air velocity in the close vicinity of the animal surface and alter the air-supply angle (Wang et al., 2018). The combination of a hybrid ventilation system and a roof-mounted evaporative cooler that blows cooled air downward to the laying area of the dairy cows is often called “Saudi barn”. For mechanically ventilated buildings, the air inlet can be used to increase the air velocity in the animal zone as well. This can be seen by the use of cross-sectional ventilation systems and tunnel ventilation for increasing convective heat loss during hot weather; much of the USA and tropical/subtropical climates are shifting towards these systems. Most of the heat stress metrics do not include the convective cooling by an increase of air velocity. Only for heavy broilers has a temperature-humidity-velocity index THVI, which takes into account air velocity at animal level, been suggested (Tao & Xin, 2003). However, this cannot be used under mid-latitude production conditions with ambient temperatures.

2.3.2. *Fogging, misting, and sprinkling systems*

These AMs cover a wide range of modes of action from wetting the animals and cooling their skins (sprinkling) to high-pressure systems which cool the indoor air adiabatically (fogging). These cooling systems produce water droplets, which cool the air by evaporation as they disperse. In general, the evaporation process depends on the droplet diameter, sedimentation velocity, and the relative humidity of the ambient air (Haeussermann et al., 2007; Su et al., 2018). The droplet diameter has a major impact on the velocity and duration of the evaporation. For high-pressure systems, with $7\ 10^5$ to $70\ 10^5$ Pa pressure used, sprays with mean droplet diameters between 10 and 30 μm diameter (fogging) can be expected, for low-pressure systems with 3102 10^5 to $5\ 10^5$ Pa droplets with mean diameters around 60 μm diameter can be expected (misting). Sprinkling systems can produce more coarse sprays and are generally operated at high ventilation rates which suggests that the amount of water evaporated to increase the humidity inside the room is negligible. The coarse droplets, there is an increased risk of water droplets reaching the ground, resulting in a low efficacy of the system and a moistening of the animal litter or ground (Hoff, 2013). Also, the amount of wastewater with sprinkling can increase considerably (West, 2003). Because sprinkler systems are often used to wet the animals directly, like a shower, air humidity is increased but their can be some negative effects on animal health.

2.3.3. *Cooled drinking water*

The cooling effect of supplying cold drinking water depends on the water intake of the animals and the temperature of the drinking water. For piglets with a body mass of 30 kg and a body temperature of 39 °C, a daily intake of 3 l of 10 °C cold water will result in a mean heat flow rate of 4.2 W. With the metabolic heat production of the piglet of 123 W, this effect of about 3.5% seems negligible. For a fattening pigs with 120 kg body mass the cooling rate by cold drinking water (15 l d^{-1}) results in 21 W which is 8.5% relative to the entire heat production of 246 W. For lactating sows with high water intake, their performance could be increased by cooled water (Jeon et al., 2006).

In addition to the energy needed to cool the drinking water, supply pipes have to be insulated. Glatz (2001) suggested flushing water pipes regularly to keep the water cool, especially during extreme heat weather conditions. Additional measures should ensure that incoming water pipes are protected from direct sunlight and that all water pipes are well insulated. Additional measures could be using ice in water tanks and shading of water tanks. The installation of an additional water-cooling unit would be an added expense.

2.3.4. *Cooled lying areas*

Heat release can be improved by conductive heat transport when bodies are in contact with cooled areas. In general, all floor areas, which are equipped with floor heating, can be used for this purpose as well. Shi et al. (2006) showed that the temperature of the sleeping area is a key factor influencing the lying behaviour of pigs: At temperatures below 26 °C, they found that more than 85% of the pigs were lying in the sleeping area. At temperatures above 30 °C this reduced to only 10–20% but at temperatures above 33 °C no pigs were found lying in the sleeping area. The cooling of the solid lying area (cooled from 24.5 °C to 20 °C at the end of the fattening period) resulted in a higher percentage of pigs lying. The cooling had no effect on the fouling of the surfaces, but it reduced the fouling of the animals (Opderbeck et al., 2020). Huynh et al. (2004) demonstrated that floor cooling significantly increased the pig feed intake and growth rate. For sows, during 12 h after the beginning of farrowing, a heated lying surface is optimal, with subsequent cooling during lactation. Both would be beneficial to reduce piglet losses around birth and increase the well-being of sows (Pedersen et al., 2013).

2.3.5. *Radiative cooling*

Radiative cooling devices use a low surface temperature to increase the radiative heat release by the surface of the animals, depending on the viewing angle and the surface temperature of the device (Curtis, 1983; DeShazer et al., 2009; Hoff, 2013). Radiative heat transfer rates are low compared to the other pathways (Cabezon et al., 2018), whereas Hoff (2013) assessed the portion of thermal radiation by 50% of the total sensible heat transfer. By such systems, the microenvironment of sows can be influenced without cooling that of the piglets, which need a warm microenvironment (Wagenberg et al., 2006). The inlet water temperature should be below 20 °C (Pang et al., 2010). Hence, cooled lying areas and radiative cooling systems can both be supplied by groundwater (Baoming et al., 2004; Jais & Freiberger, 2006; Li et al., 2011). By such systems, the energy demand can be limited to pumping the water.

2.3.6. *Thermoregulation with water wallows*

In addition to the advantages offered by wallows for the well-being of pigs, they enable several heat release mechanisms. Of highest importance is the evaporative cooling after wetting the skin, as the preferred mechanism to cope with heat stress. Thermoregulatory behaviour is a function of effective environment, pig body mass, health status, stocking density, etc. Huynh et al. (2005) found, that the use of wallows is initiated at temperatures exceeding 16 °C. Culver et al. (1960) showed that the use of a wallow reduced the rise in the respiration rate, but was not as effective as evaporative cooling by water sprinkling, especially at temperatures above 28 °C. Even if the wallow was drained frequently, and freshwater was added daily, there was considerably difficulty keeping the wallow clean, hence increasing the risk of communicable diseases. The benefit of wallows in pig husbandry was reviewed by Bracke (2011). Little scientific evidence exists for other functions of wallowing besides thermoregulation like sunburn protection and the removal of ectoparasites. The impact on pork quality by a reduction of heat stress as well as by the use of shallow pools like wallows was shown by de Mello et al. (2017). Besides the running costs incurred for cleaning and water consumption, the integration of wallows in livestock buildings with a small or medium group size is difficult to realize without a reduction in the available lying area for the pigs. Thus, from a hygienic point of view, the integration of a wallow into an intensive indoor housing system is usually considered risky regarding the diffusion of pathogens.

2.4. Livestock management

2.4.1. Reduction of stocking density (SD) during the summer season

The sensible heat load caused by the animals is the reason for using a higher indoor temperature compared to the outside (inlet air) temperature. To reduce this load the stocking density can be reduced. The amount of possible heat stress reduction was calculated for fattening pigs in an Austrian case study (Schauberger et al., 2019). A reduction to 80% (SD80%) and 60% (SD60%) of the design value (100%) of the livestock building during summer, led to a rather low performance in heat reduction and additionally to higher opportunity costs caused by lost revenue. White et al. (2008) showed that both temperature and spatial allocation affected growth performance and carcass quality. Almost 50% of the negative growth performance effects of temperature can be ameliorated by a 28% increase in spatial allocation. The reduction in heat release for broilers (Aradas et al., 2005; Kim et al., 2016) and turkeys (Jankowski et al., 2014) has also been discussed. In addition to the stocking density, a reduction of the live mass at slaughter can also be realised (e.g. Aradas et al., 2005).

2.4.2. Increasing the summer ventilation rate

The major goal of the summer ventilation rate is to remove the sensible heat release of the animals and to limit the temperature difference between outdoor and indoor temperature to a certain extent (about 3 K). The summer ventilation rate depends on the regulations and standards in various legal norms. In Table 1 the wide variety of values found is summarised for fattening pigs. Due to the use of cross-section ventilation regimes for hot climate zones to increase the air velocity, the summer ventilation rate, which is based on the sensible heat balance, is losing its relevance. A study by Schauberger et al. (2019) revealed the consequences of doubling the ventilation rate from 100 to 200 m^3 h^{-1} on the occurrence of heat stress in fattening pigs. The doubling of the ventilation rate has an effect similar to that of the reduction of animal density by 50% limited opportunity costs. However, the increase of the ventilation rate typically needs additional investments to adapt the capacity of the fans. Increasing the animal-specific ventilation rate from 47 m^3 h^{-1} to 66 m^3 h^{-1} per ewe, a significant improvement on animal performance was achieved (Sevi et al., 2003).

2.4.3. Inversion of the diurnal feeding and resting pattern

The animals show a distinct diurnal patterns of the activity, predominantly influenced by the feeding system (ad libitum or restricted feeding) (Pedersen & Takai, 1997). In general, the period of high animal activity coincides with the maximum of the outdoor temperature (Fig. 4). The diurnal variation of activity causes a diurnal variation of the sensible heat release of the animals in a range of ±20%. Shifting the feeding and resting time pattern by about half a day, the maxima of the two diurnal patterns can be separated. The modification of the time pattern can be achieved by a change of the lightning regime inside the building. While windows must be equipped with blinds, only artificial light has to be used for the feeding time during the night. This shift of activity and rest periods must be paralleled for all individual compartments of a livestock building to avoid interference, especially by the noise of the feeding system and the animals. While feeding during night-time would increase labour costs, a shift of feeding time to cooler periods of the day should be evaluated with a high priority at least for feedlots (Stokes & Howden, 2010).

Table 1 – Design value standards for the summer ventilation rate (m^3 h^{-1}) for fattening pigs in various countries.

Body mass (kg)	Ventilation rate (m^3 h^{-1})	Country	Source
70 to 100	17	USA/Cold climate	MWPS-32 (1990)
	60	USA/Mild climate	
	205	USA/Hot climate	
100	99	Germany	DIN 18910 (2017)
120	119	Austria	Santonja et al. (2017)
~120 (100 d)	60–80	The Netherlands	Santonja et al. (2017)
~120	100	Denmark	Santonja et al. (2017)
~120	65	France	Santonja et al. (2017)
~120	120	Spain	Santonja et al. (2017)
~120	115	Germany	Santonja et al. (2017)
~120	80	Belgium (FL)	Santonja et al. (2017)

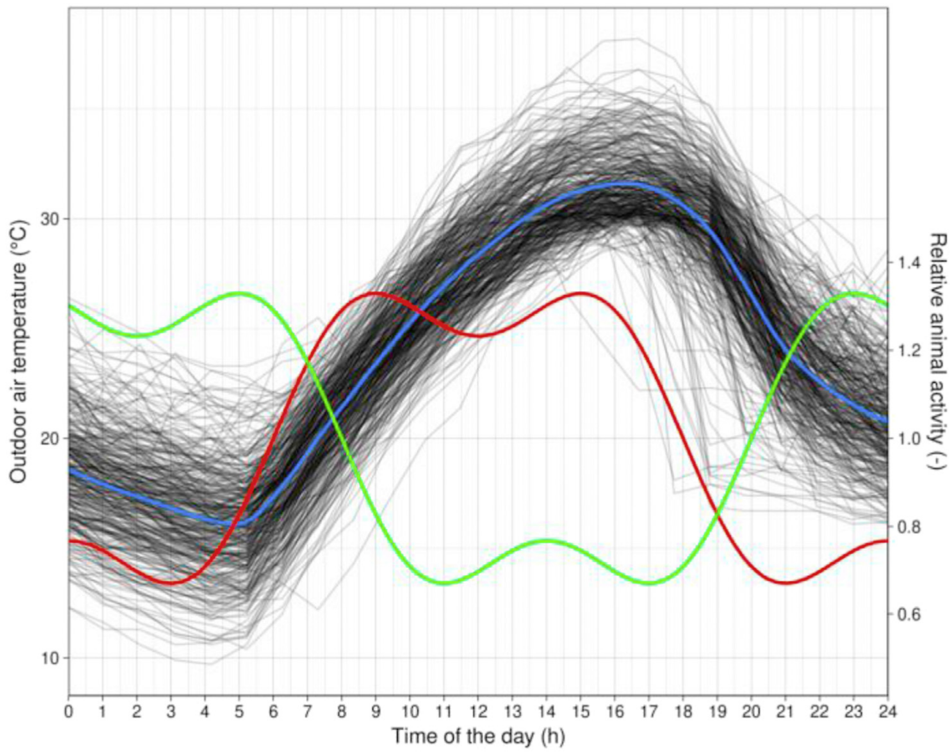

Fig. 4 – Diurnal variation of the temperature of heat days (daily maximum > 30 °C; blue line: average) between 1981 and 2017 and the time pattern of the relative animal activity for the conventional system, which describes the conventional feeding and resting time (red line) and the suggested time pattern by a shift of 10 h (green line) (Schauberger et al., 2019).

2.4.4. *Thermotolerant and adapted breeds*

To minimise economic losses caused by heat stress, a long-term option is genetic selection of genotypes with greater heat tolerance. Genetic variation exists with respect to heat stress-coping ability (Zumbach et al., 2008), so that selection for appropriate traits e.g. rectal temperature, residual feed consumption, respiratory rate or cutaneous temperature, is possible (Gourdine et al., 2017).

Animals with a high metabolic heat production are susceptible to heat stress (Ames et al., 1981), hence the usual genetic selection for high growth rates is in contrast to heat tolerance in both pigs and chicken (Renaudeau et al., 2011). Over the last decades, breeding for lean growth led to an increase of the metabolic heat production and a lower resilience against heat stress (Brown-Brandl et al., 2001). Heat production by conventional pigs increased by 17.4% between 1988 and 2004, in parallel to increased average daily weight gains (Brown-Brandl et al., 2004).

In the future, breeding objectives including improved heat tolerance could be aimed at by selecting for production efficiency under heat stress challenge (Merks et al., 2012), with heat production and dissipation, as well as the occurrence of heat shock proteins being involved in the underlying mechanisms (Renaudeau et al., 2004). Directing blood flow in the skin for thermal regulation might have a high impact on resilience to heat stress (Moran et al., 2006). A similar effect of increased sensitive heat loss may result from the introgression of two major genes in poultry, the naked neck gene and the frizzle gene (Lin et al., 2006; Pilling and Hoffmann, 2015; Yunis & Cahaner, 1999).

Differences between genotypes concerning their susceptibility to heat stress may involve differences at the cellular level (Bambou et al., 2011) and in immune and stress response (Cross et al., 2018). Genetic differences in the change of feeding behaviour at different THI conditions for growing and finishing pigs could also indicate differences in heat resilience (Cross et al., 2018).

2.4.5. *Feeding strategy*

Adjusting diet composition can support the ability of animals to cope with heat stress. Overall, two main nutritional strategies may help in alleviating heat stress: (1) increasing dietary protein and energy density in order to compensate for reduced intake of feed, (2) feeding diets with low heat increment (Renaudeau et al., 2011). During heat stress, animals reduce feed intake in order to balance metabolic heat production with the capability to dissipate heat. Heat increment is estimated to be 30% of the ingested metabolisable energy (ME) in mammals (Smith et al., 1978), and reduction in feed intake is one of the most important coping mechanisms during heat stress (Renaudeau et al., 2011). Less heat energy is produced by feeding low-protein diets (Just, 1982; Noblet et al., 1987, 1994), because of less protein breakdown, urea synthesis and body protein turnover (Roth et al., 1999), particularly if the amino acid profile of the protein is close to ideal (Lin et al., 2006). Supplementing

Table 2 – Overview of the investigated adaptation measures AMs, the method of the efficacy assessment (model result M/ expert estimate E) and the range of the modelled and estimated (in brackets) efficacy.

Adaptation measure/Abbreviation	Method	Efficacy (%) in reduction of heat stress parameters compared to reference system
Air treatment		
Cooling pads CP	Modelling	61–86
Cooling pads plus heat exchanger CPHE	Modelling	74–92
Earth air heat exchanger EAHE	Modelling	93–100
Heat exchanger by ground water	Expert	(82–97)
Building		
Orientation	Expert	(4–7)
Green façade/roof sprinkling	Expert	(3–6)
Insulation of the buildings	Expert	(4–8)
Shading by plants	Expert	(3–8)
Animal level		
Increased air velocity	Expert	(10–24)
Sprinkling	Expert	(22–44)
Fogging	Expert	(42–62)
Cooled drinking water	Expert	(5–11)
Cooled laying area	Expert	(20–40)
Radiative cooling	Expert	(10–28)
Wallow	Expert	(23–42)
Management		
Stocking density SD80%	Modelling	4–6
Stocking density SD60%	Modelling	8–11
Maximum ventilation rate	Modelling	23–44
Time shift of the activity pattern	Modelling	34–51
Adapted breeds	Expert	(13–30)
Dietary and feeding strategy	Expert	(20–30)

The efficacy of the investigated AMs is summarised in Table 2, showing the simulated and the estimated range (in brackets). The graphical presentation is depicted in Fig. 6.

diets with isolated essential amino acids may therefore be a promising feeding management measure. However, there is lacking agreement on the extent and underlying mechanisms of change in amino acid requirements of broilers experiencing heat stress (Gonzalez-Esquerra & Leeson, 2006).

Substituting carbohydrates by fat as a dietary energy source can further decrease heat production and may also allow to balance a decrease in feed intake (Noblet et al., 1994, 2001; Renaudeau et al., 2012). A reduction of dietary crude protein might not affect the composition of carcass and growth as long as an optimal ratio is maintained between net energy and essential amino acids. Basic postabsorptive changes in heat-stressed pigs include higher circulating insulin concentrations; resistant muscle and sensitive adipose tissue responsiveness result in a greater accumulation of carcass lipid than muscle protein accretion (Pearce et al., 2013).

High fibre content in the diet is unfavourable in heat-stressed pigs and poultry due to the high heat production rate during digestion (Spencer et al., 2005). The impact of dietary fibre on metabolic rate, feed consumption and physical activity is highly dependent on the fibre characteristics with respect to botanical origin and texture, showing the relevance of which fodder plant is used (Rijnen et al., 2003).

Because feed intake is reduced during heat stress, an increase in concentrations of vitamins and minerals in the diet might be beneficial (Lin et al., 2006).

3. Assessment of the efficacy of the AMs

Farmers require information on the likelihood and severity of future climate extremes, their effects on the indoor climate and the efficacy of AMs in order for them to take suitable adaptation decisions. The efficacy of AMs is described by measures to reduce the heat stress for farm animals in a quantitative way by the use of heat stress parameters (e.g., the exceedance of a threshold or the area under the curve of a threshold). In addition to the inside air temperature of the livestock building, the temperature-humidity index was selected here to define the threshold values. If no quantitative values are available, a qualitative assessment was used instead. This chapter evaluates the efficacy of AMs in regulating indoor climates and livestock wellbeing based on scientific literature and expert assessments.

3.1. *Method to determine the efficacy of the AMs*

The assessment of the efficacy of some of the AMs discussed in section 2 was based on the simulation of a reference livestock building for fattening pigs for the time period 1981 to 2017 (Mikovits et al., 2019). This reference system was used as a baseline, representing a typical livestock building for growing-fattening pigs in Central Europe for 1800 heads, divided into 9 sections with 200 animals each. The

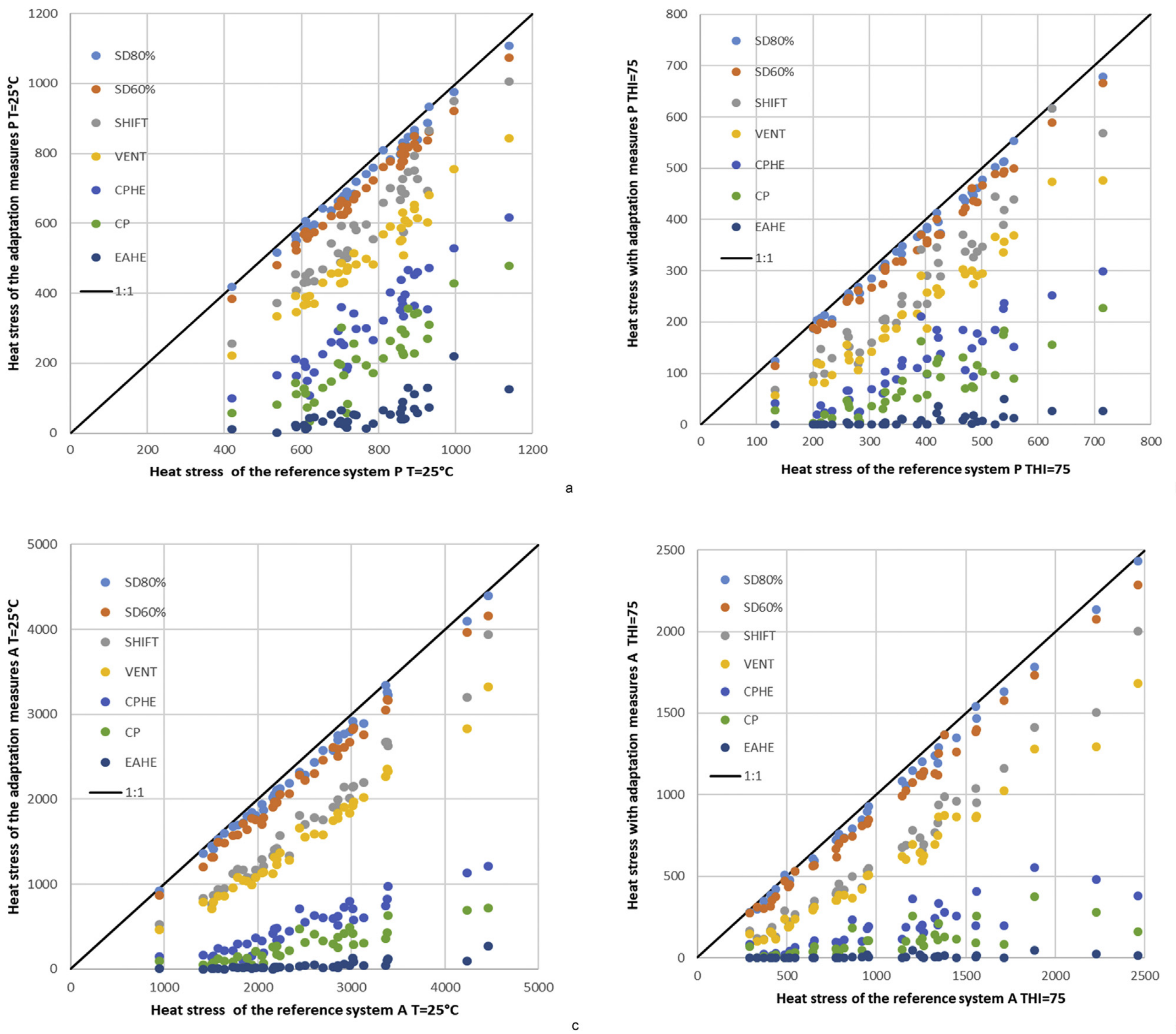

Fig. 5 – Annual sums of simulated heat stress parameters for adaptation measures as a function of a reference livestock building, calculated for a livestock building for pigs between 1981 and 2017. Heat stress parameters: Exceedance frequency P (h a^{-1}) (upper panel, a and b) and area under the curve A (lower panel, c and d) for an indoor temperature threshold of 25 °C (left side, a and c) and a THI threshold of 75 (right side, b and d). Adaptation measures: stocking density SD80%, stocking density SD60%, shift of the resting and activity periods (SHIFT), doubling the ventilation rate (VENT), cooling pads and heat exchanger CPHE, cooling pads CP, and earth air heat exchanger EAHE.

applicability of some of the discussed AMs (CP, CPHE, EAHE, SD80%, SD60%, VENT, and SHIFT) was investigated by Vitt et al. (2017), the efficacy was calculated by the simulation as well (Schauberger et al., 2019). These AMs were used as a point of reference to assess the performance of all the other AMs discussed in this article which were not included in the previous calculations considered so far (Table 2 and Figs. 5 and 6).

Efficacy is assessed as the reduction of the heat stress metrics due to the implementation of the respective AMs. The reduction factor is calculated by the annual sum of a certain heat stress parameter of the simulation period 1981 to 2017 for a selected AM and for the reference system REF (Schauberger et al., 2019). The reduction factor was calculated for the exceedance probability and the area under the curve for the following heat stress parameters: the exceedance (number of hours per year) for (1) the inlet air temperature of 25 °C and (2) the temperature-humidity index of 75. By the simulation of the AMs, the reduction factors, which are based on the four heat stress measures (exceedance frequency P (h a^{-1}) and area under the curve A for air temperature and T = 25 °C and THI = 75) are available. Efficacy is expressed by the range (minimum, maximum). For AMs for which no model calculations are available, the reduction factor was estimated based on the experience from experts in the field of agricultural engineering and veterinary medicine, asking for the expected minimum and maximum value.

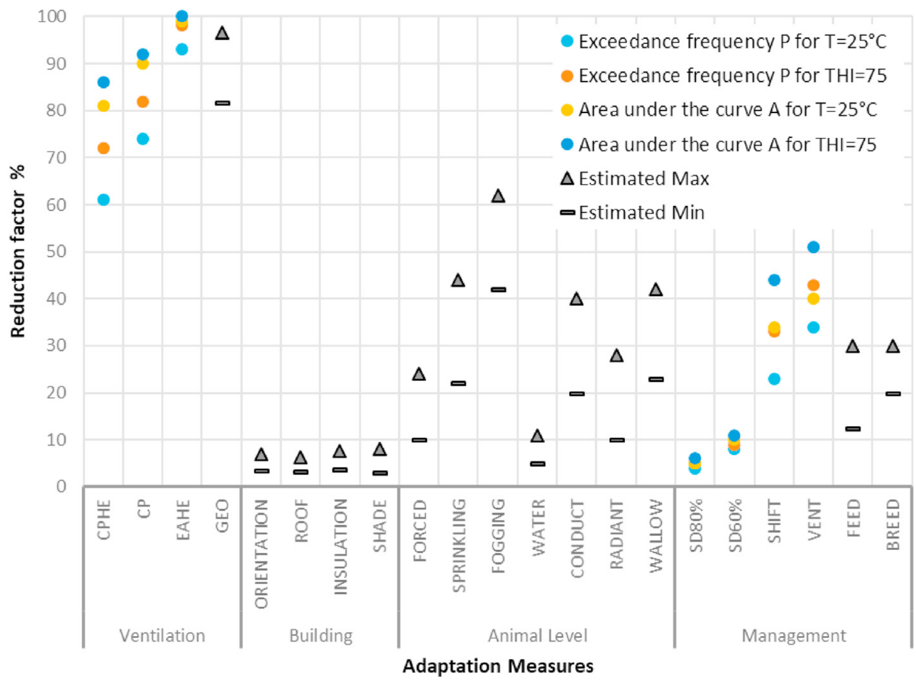

Fig. 6 – Reduction factor of heat stress determined for adaptation measures using simulated (Exceedance frequency P (h/a) and area under the curve A for an indoor temperature threshold of 25 °C and a THI threshold of 75) and estimated values. The following AMs are presented: Ventilation system: cooling pads and heat exchanger CPHE, cooling pads CP, and earth air heat exchanger EAHE, and geothermal cooling by groundwater (GEO); Building: orientation of the building (ORIENTATION), green façade/roof sprinkling (ROOF), insulation of the buildings (INSULATION), shading by plants (SHADE); animal level: increased air velocity (FORCED), sprinkling (SPRINKLING), fogging (FOGGING), chilled drinking water (WATER), cooled laying area (CONDUCT), radiative cooling (RADIANT), wallow (WALLOW); management: stocking density (SD80%), stocking density (SD60%), temporal shift of the resting and activity periods (SHIFT), doubling the ventilation rate (VENT), feeding strategies (FEED), and adapted breeds (BREED).

3.2. *Efficacy of the simulated AMs*

The efficacy of the seven investigated AMs was simulated for Central Europe. Three energy saving AMs cool the inlet air and are part of the ventilation system (CPHE, CP, and EAHE). The other AMs are related to the management of livestock: a reduction of the stocking density (SD80% and SD60%), the doubling of the summer ventilation rate, and the temporal shift of the resting and activity period. These seven AMs were used here as a point of reference for all other AMs to estimate the efficacy by a comparison of the cooling methods and the expected cooling performance.

The reduction of the annual sums of the values of the four heat stress parameters of the simulated AMs is shown in Fig. 5. They are sorted in descending order using the reduction factor. The linear slope of the temporal trend was used to evaluate the resilience against global warming of the livestock system (Schauberger et al., 2019). If the linear slope of a heat stress parameter for a system with a certain AM is shallower than for the reference system, then the resilience is increased by the AM. The resilience of the AM is proportional to the reduction factor, which means the higher the reduction factor, the shallower the slope (Schauberger et al., 2019). The first three AMs are based on cooling the inlet air (CPHE, CP, and EAHE) and show the highest efficacy, not only reflected by the reduction factor but also by the resilience. EAHE showed the best performance with a reduction of 93–100%, followed by the CP with 74–92% and the CPHE with 61–86%. The shift of the time pattern (34–51%) and the doubling of the ventilation rate (23–44%) are less effective than those of cooling the inlet air.

The reduction of the stocking density to 80% and 60% (SD80% and SD60%) reduces the heat stress only in the range of 4–11%. These two AMs show a slope, which is close to the line of identity (1:1), which means that the resilience is about the same as the reference building without AMs. The efficacy of the three AMs SD80%, SD60% and the doubling of the summer ventilation rate can be compared directly. The first two AMs reduce the release of sensible heat by 20% and 40%, the last one by 50%. The discrepancy between the three methods is caused by the duration over the year. The reduction of the stocking density is only effective during the hottest period of the year, whereas the high summer ventilation rate is effective also during spring and autumn, where high outdoor temperatures can occur as well.

3.3. *Estimation of the efficacy of the remaining AMs*

The last AM in the group of air treatment systems (ventilation systems) investigated is a heat exchanger which uses groundwater as a transport medium between the inlet air and the earth. During summertime, the earth acts as a heat sink, during wintertime the soil is a source for heat. The efficacy depends on the availability of groundwater and the efficacy of the water–air heat exchanger. In principle, this system is similar to the earth-air heat exchanger. Therefore, the assumed efficacy is close to that of the EAHE.

The efficacy of the three AMs for buildings, the orientation of the building, green façade/roof sprinkling, and insulation of the buildings depends strongly on the design of the livestock building (Bjerg et al., 2019). Confined livestock buildings and the ventilation systems are aligned predominantly to guarantee the lower limit of the thermo-neutral zone of the animals (Vitt et al., 2017). Therefore they are frequently termed "warm confinement livestock buildings" (Gillespie & Flanders, 2009; Zulovich, 1993). Due to a high ventilation flow rate during summertime, the coupling between outdoor and indoor situation is very effective and the heat flow through the building shell is limited. Further on the time lag of the heat flow through insulated elements (wall, ceiling etc) is in the range of 8–12 h for a south orientated wall with a high attenuation of the amplitude of the surface temperature (Asan & Sancaktar, 1998; Ozel & Pihtili, 2007). The efficacy of these AMs was estimated to be between 3 and 8% (Table 2). The shading of windows by plants can reduce the incoming solar radiation. During summer and around midday, this can be a relevant contribution to the sensible heat load of the animals which occurs synchronously to the outdoor air temperature. The efficacy was estimated to be in the range of 3–8% (Table 2).

On the animal level, the efficacy of fogging by high-pressure systems can be compared directly to that of the direct evaporative cooling by CP. The major challenge for such systems is the prevention of soaking the bedding material and the increase in water amount. In many cases, this is controlled by intermittent fogging. The side effect of this AM is the increase of the humidity of the indoor air. The efficacy of fogging was estimated to be lower than that of CPs with 42–62% (Table 2).

Systems with low water pressure such as sprinkling or shower systems differ from each other by the size of the droplets. With increasing droplet size caused by lower water pressure, the cooling efficacy is reduced by lowering the evaporative cooling. This means, that the cooling changes from air cooling to direct cooling of the animals by the water droplets (Bjerg et al., 2019). For some cases, Hoff (2013) demonstrated, that sprinkling can be more effective at cooling pigs than CPs. However, the efficacy is much lower compared to fogging with a high-pressure system. The efficacy was estimated with 22–42% (Table 2), depending on the water pressure. Insufficient pen coverage (water dispersion) and amount of water (nozzle type and water pressure) are more likely to reduce heat stress reduction potential than water pressure alone.

Systems with forced ventilation increase the convective heat release from the animals by forced convection. The additional air velocity (due to additional fans) can partially compensate for the limited temperature gradient between skin and air temperature. Therefore the efficacy depends strongly on the air velocity at animal level. The increase of only the convective pathway of heat release was estimated by an efficacy of about 10–24%. The other two AMs which increase the conductive and the radiative pathway of the sensible heat release of the animals are the cooling of the lying area and a cool surface above the animals. Similarly, the efficacy was estimated to be between 10 and 40%. The last AM is the cooled drinking water. Its efficacy depends on the daily water intake and water temperature. The first parameter depends on the type of feeding (liquid or dry), the latter on the insulation of the pipes. The estimated efficacy was 5–11%.

Wallows can only be used for pigs. Their accessibility is a major limitation and leads to expert estimates of the lower limit of the efficacy of 23%. The upper limit could reach a value close to the showers and sprinkling systems with 42%.

4. Discussion

Global warming has a considerable impact on the occurrence of heat stress inside confined livestock buildings. The temporal trend of an Austrian case study shows a significantly increased frequency over the last four decades (Mikovits et al., 2019). Several AMs are in use to alleviate heat stress and to improve the thermal environment of the animals. This improvement includes several aspects: (1) appropriate thermal environment in the thermo-neutral zone is relevant for animal welfare and the concept of "life worth living" (Mellor, 2016) which is an integral part of the sustainability criteria of livestock production systems (Tarazona et al., 2020), (2) optimum thermal environment supports optimal feed conversion and productivity of the animals. (3) improved productivity can also be seen as a reduction in GHG emissions in the sense of sustainable intensification (Garnett et al., 2013; Silva et al., 2017). The higher the productivity of the livestock system the lower the footprint of the food production (Rivera-Ferre et al., 2016), and (4) a reduction of the heat stress-related economic losses (St-Pierre et al., 2003).

The performance of AMs can be investigated by empirical measurements, which are conducted for a certain livestock building, a distinct meteorological situation and other boundary conditions during the measuring period, which limit the universal validity. The advantages of a modelling approach (Mikovits et al., 2019; Schauberger et al., 2019), which was used here for the simulation of the AMs in comparison with measurements are many: (1) the model can be applied to other geographical sites by the use of corresponding meteorological datasets, (2) near future scenarios can be assessed by the extrapolation of the linear trend in a long time series (e.g., 1981 to 2017) as robust predictions (Hendry & Pretis, 2016), (3) optimisation of the design values (e.g., for the EAHE) can help to improve the efficacy relative to the climatic situation for a certain site, (4) future developments of system parameters can be considered (e.g., market demand for heavier pigs), (5) the combination of several AMs can be simulated and (5) the reference livestock building can be adapted to local conditions and requirements.

In this investigation, efficacy modelling results for several AMs used as benchmarks were assessed by expert estimates where modelling is inappropriate due to lack of data, incomplete knowledge or methodological constraints.

To quantify the cooling performance of AMs which modify the microclimate of the animals, often called animal occupied zone, more advanced models are necessary which include the thermoregulation of the animals. Such models can quantify those AMs which modify the sensible and latent heat release of the individual animal, like cooled lying areas or radiant cooling covers. Bjerg et al. (2019) emphasised the need to also simulate small scale AMs on animal level. Such animal-based models have to be coupled with the models on housing level (Bjerg et al., 2018).

As the selected reference building serves as a baseline, it has an important impact on the quantification of the efficacy of the simulated AMs. In our simulation, the reference building is a confined livestock building with a well-insulated building shell and a mechanical ventilation system, typically used in Central Europe. In the year 2000, about 3/4 of all pig farms in Germany had fully (45%) or partly (30%) slatted floors (Weber, 2003). About 93% of fattening pigs are kept on fully or partly slatted floors in Austria today (Pöllinger et al., 2018). In 2019, more than 94% of pigs in Austria are reared in systems without litter material (Weißensteiner & Winckler, 2019), which require a mechanical ventilation system. In Southern and Central Italy, for example, the proportion of uninsulated roofs (64%) and naturally ventilated buildings (64%) is much higher (Arcidiacono, 2018). This has to be taken into account if the modelled and the estimated values of the efficacy of AMs are transferred to other regions.

Therefore the efficacy of certain AMs strongly depends on the type of livestock building (Arcidiacono, 2018). For the simulation, a reference building was selected which is used predominantly for pigs and poultry in a temperate climate like in Central Europe. It is well insulated and equipped with a mechanical ventilation system. The simulated AMs and the derived efficacy were related to this type of buildings. As an example, the efficacy of a sprinkled roof is much greater for less insulated buildings as compared to our reference system with high U values, even for the roof. Nearly all AMs which affect the livestock building will have a considerable higher efficacy for non-insulated buildings as compared to the reference building. This shows that a model approach, which is adapted to the regional situation and run by meteorological data for that region, will give reliable results.

In the group of AMs, which are related to livestock management, not only technical, management, or material-based AMs can be included, but also the cooperative behaviour of farmers and the stock persons. This can include that animals remain undisturbed during the hottest time of the day (afternoon and early evening), to adapt the work schedules to carry out routine work (e.g., practices that require animal handling, such as vaccination) early in the morning or at night. These management principles cannot be quantified and assessed in their impact to reduce heat stress but should be included in the standard operation procedure of a livestock farm (Hy-Line International, 2015).

All AMs can be divided into groups relative to their costs, complexity, knowledge required by the farmers, and the time scale of implementation (Holzkämper, 2017). AMs related to management can be applied in the short term, such as SD60%, SD80% and shifting activity patterns. They can be seen as incremental responses and can be chosen autonomously by farmers in response to observed changes and based on local knowledge and experience. Any adaptation response is subject to the sensitiveness and awareness of farmers towards climate change (Mitter et al., 2019). Even investments in insulation or ventilation are considered as incremental adaptation measures autonomously implemented by farmers in an Austrian survey among agricultural experts (Mitter et al., 2018). These management AMs can be adjusted from year to year and require only low investments. The second group are long-term adaptations with a systemic response that need strategic planning (Mitter et al., 2018). Planning for new livestock buildings requires foreseeing options for the eventual implementation of potential AMs (Mitter et al., 2019). Therefore, the data for the design and planning of AMs have to be known early enough by farmers, consultants, and veterinarians to ensure a high level of resilience in livestock production (Walker et al., 2013). In this context, air treatment devices (e.g. CP, CPHE, EAHE, and geothermal cooling) and all AMs which are related to the building (orientation, roof treatment, and insulation) are long-term systemic measures and imply substantial investments. The AMs on animal level can be seen as short to mid-term incremental adaptations. Hallegatte (2009) identified five attributes that can contribute to the robustness of AMs. They distinguished between no-regret strategies, which are able to cope with climate uncertainty. Even in the absence of heat stress, these strategies would yield benefits (e.g., EAHE warming the inlet air during wintertime). Reversible strategies are more flexible, keeping costs as low as possible. Most of the livestock management measures are such strategies. Safety margin strategies reduce vulnerability at null or low costs (e.g., the orientation of the building). Soft strategies can ensure institutional tools like the adaptation of standards and regulations (e.g., increasing the summer ventilation rate). Due to the time trend of the climate change effects, the reduction of decision-making time horizon can be important. By air treatment measures, the increase of the vulnerability by global warming can be shifted by several years which was shown by Schauberger et al. (2019).

Simulations were performed only for single AMs. Combinations of several AMs which complement one another were not investigated. The simulation of several AMs would be helpful to optimise the design values of such systems. In addition to the modification of thermal climate and air quality, also economically factors such as electrical energy demand can be calculated (Mikovits et al., 2019).

5. Conclusions

This analysis can be seen as a semi-quantitative assessment of AMs as a support for management decisions. The efficacy of adaptation measures ranges from almost zero (for measures which reduce the sensible heat load of the livestock building; e.g., reduction of the stocking density) to highly effective methods (i.e., reduction of the inlet air temperature by air treatment systems). To select an appropriate adaptation measure, the efficacy of potential measures has to be determined. For some of those, their efficacy was assessed using a simulation model. Such a model approach has the advantage that it can be adapted to different climate conditions (i.e., using meteorological data) and different barn infrastructure and husbandry practises, which vary by regional traditions. Most of the models which are used to simulate the indoor climate can be reduced to thermal parameters and air quality. The subsequent assessment of the productivity of the animals (e.g., average daily gain, mortality, feed conversion ratio) is carried out in a post-processing mode without any feedback to the simulation models. If animal productivity and an economic evaluations are to be included in such simulation models, a seamless model design should be realised. To improve the explanatory power of such an evaluation of adaptation measures, an economic evaluation should be completed for such an investigation: The investments and the running costs of such adaptation measures should be contrasted with their efficacy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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