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Economic risk assessment by weather-related heat stress indices for confined livestock buildings: a case study for fattening pigs in Central Europe ‡

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‡ Dedicated to our colleague, Dr. Knut Niebuhr

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Abstract

In the last decades farm animals kept in confined and mechanically ventilated livestock buildings are increasingly confronted with heat stress (HS) due to global warming. These adverse conditions cause a depression of animal health and welfare and a reduction of the performance up to an increase of the mortality. To facilitate sound management decisions, livestock farmers need relevant arguments, which quantify the expected economic risk and the corresponding uncertainty. The economic risk was determined for the pig fattening sector based on the probability of HS and the calculated decrease in the gross margin. The model calculation for confined livestock buildings showed, that HS indices calculated by easily available meteorological parameters can be used for assessment quantification of indoor HS, which is so far difficult to determine. These weather-related HS indices can be applied not only for an economic risk assessment but also for a weather-index based insurance for livestock farms. Based on the temporal trend between 1981 and 2017, a simple model was derived to assess the likelihood of HS for 2020 and 2030. Due to global warming, the return period for a 90-percentile HS index is reduced from 10 years in 2020 to 3-4 years in 2030. The economic impact of HS on livestock farms was calculated by the relationship between an HS index based on the temperature-humidity index (THI) and the reduction of the gross margin. From the likelihood of the HS and this economic impact function, the probability of the economic risk could be determined. The reduction of the gross margin for a 10 year return period was determined for 1980 with 0.27 € per year and animal place and increased by the 20-fold to 5.13 € per year and animal place in 2030.

1. Introduction

Livestock production is threatened by various effects of global warming such as the availability of feed, pasture and the reduction in feed yield from drought [1-3], new diseases and new transmitting vectors [4-8], and heat stress (HS). For livestock, which is frequently kept inside confined livestock buildings such as pig and poultry, HS is worsened by higher temperature and humidity compared to the outside situation, due to the release of sensible and latent heat of the animals [9]. Therefore, HS is one of the major threats for conventional, intensive pig and poultry production. In confined livestock systems, HS will reduce the gross margin, which can also be seen as an impairment of the economic resilience of farms [10]. The economic risk assessment for HS scenarios requires information about (1) the identification of an appropriate predictor for HS, mainly HS metrics appropriate for the considered animals and their barn environment [11], (2) the quantification of the likelihood of this predictor, which depends on the stochastic outside situation influenced by global warming and the resulting thermal situation inside the livestock building, which can be modelled with some confidence [9], (3) the bio-physical impacts of HS on livestock productivity [12] with some uncertainty due to insufficient empirical data age and interactions with other environmental (e.g. diets) and physical conditions (e.g. health status). Despite issues of livestock well-being, pig farmers risk economic losses from an increase of feed conversion ratio, growth rate and other productivity traits, semen quality as well as infertility, reproductive disorders, or increasing mortality [3,10,13-15].

A common measure of the risk associated with a specific environmental situation is the product of the likelihood of this situation and its impact. Focusing on only one of these two factors or considering them only sequentially is insufficent. For a proper risk assessment, the interaction between both matters. King, *et al.* [16] point out that there are several problems and shortfalls of quantitatively characterising risks. Inadequate quantifications are caused by a high sensitivity to uncertainties and incomplete assumptions. They are also likely to be systematically biased towards underestimation of risk, as they tend to omit a wide range of impacts that are difficult to quantify. The authors emphasized that risks should always be assessed in relation to objectives of analysis. In the case of climate change and confined livestock keeping of pigs and poultry, one of the relevant objectives is related to the evaluation and finally the application of adaptation measures to cope with undesirable weather impacts [17-21].

The prediction of HS for farm animals can be performed using several HS metrics [22-24]. Some of them are suitable for animals kept outdoors or on pasture, including wind velocity and solar radiation; others were developed for indoor conditions of confined livestock buildings. Several HS indices are based solely on the air temperature related to the upper critical temperature of the animals, some include humidity (e.g., the temperature-humidity index THI). More complex indices like the enthalpy concept, proposed by Beckett [25] and later refined by others [26-28], or specific indices for fattening pigs [29], are not widely used.

In the context of an economic risk assessment, three preconditions can be identified for the use of HS indices: (1) The quantification of HS inside a livestock building requires models, which take into account the complex relationship between the meteorological outdoor situation, the thermal features of the building, the ventilation system, and the livestock as a source for sensible and latent heat [9,30,31]. (2) The predictors for impact functions, which quantify the effect of HS on the performance of the animals (feed intake, average daily gain, feed conversion ratio, morbidity and mortality etc.), are predominantly the air temperature and the THI. More complex HS indices are inappropriate to describe such relationships due to lacking empirical validation. (3) Economic indicators shall adequately describe forgone revenues and both cost reductions and increases. In this respect, weather-related HS indices were analysed according to a risk assessment, which can be performed also with the use of meteorological data of a weather station in the close vicinity of the livestock building.

The increase in the frequency of hot days and heat waves in recent decades due to global warming has increased the likelihood of the situations that cause HS [32-37]. Farmers require information on the likelihood and severity of future HS specific for farm animals in order to plan for adaptation e.g. when investing in new livestock housing. The likelihood of the occurrence of a certain HS index can be quantified by a probability density function, which is defined by the temporal trend (caused by global warming) and a stochastic component [37].

The reaction of animals to the occurrence of HS is partly known for several output traits of livestock production, which impact both variable costs or the revenue (e.g., average daily gain, feed conversion ratio, milk yield, egg production (number and mass), water demand, farrowing rate, litter size, meat quality, mortality). A main challenge is to define a mathematical function with a certain HS index as a predictor for a given livestock system that consistently represents all these traits in impact functions.

The economic risk due to HS can be analysed by the use of the weather-Value-at-Risk (weather-VaR) concept, proposed by Toeglhofer, *et al.* [38]. They adapted the VaR concept as an economic risk measure of the maximum potential loss within a given confidence interval, which is determined by the weather. In this article, we use the weather-VaR to describe the economic impact of heat stress on the gross margin of fattening pigs. We assume changes in gross margins as an appropriate measure for economic risks since we do not consider investment decisions (e.g. adaptation) but analyse the economic impacts from adverse weather events.

The assessment of the economic risk for confined livestock due to HS will be demonstrated for a pig fattening operation located in Central Europe. The analysis is based on the simulation of the indoor climate inside a reference livestock building for fattening pigs [9]. The likelihood of HS from several HS indices is used to quantify the economic risk of these environmental constraints. The presented case study is outlined along the following research questions: (1) How can weather-related indices be used in an economic risk assessment? (2) What is the impact of global warming on the likelihood of weather-related HS indices in Central Europe? (3) What is the economic impact of global warming related HS on fattening pigs? (4) What can we learn, including conceptual uncertainties, from this case study for other locations and production systems?

2. Material and Methods

2.1 Meteorological data

For the calculation of the indoor air conditions, such as air temperature and humidity, meteorological data on an hourly basis are needed. The Austrian Meteorological Service ZAMG (Zentralanstalt für Meteorologie und Geodynamik) compiled a reference time series based on representative observational sites in the vicinity to the city of Wels (48.16°N, 14.07°E) for the period 1981 to 2017, with a temporal resolution of one hour.

2.2 Indoor climate model of a reference pig building

The indoor climate of the pig building was simulated by a steady-state model which calculates the thermal indoor parameters (air temperature and humidity) and the ventilation flow rate. The thermal environment inside the building depends on the livestock, the thermal properties of the building, the ventilation system, and its control unit. The core of the model is the calculation of the sensible heat balance of a livestock building [9,39,40]. The model calculation was performed for a typical livestock building for fattening pigs in Central Europe for 1800 head, divided into 9 sections, with 200 animals each. The system parameters, which describe the conventional reference system (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 a conventional livestock building [9]

	Parameter	Value
Animal		
	Body mass m	30-120 kg
	Service period (building emptied for cleaning and disinfection) per fattening period	10 days
Building		
	Area of the building oriented 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 oriented 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_C	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 [41]	8.62 m^3 h^{-1}
	Maximum volume flow rate, V_{max}, by maximum temperature difference between indoor and outdoor of 3 K [41]	107 m^3 h^{-1}

For an all in/all out production system, an animal growth model describes the increase of the release of energy and CO_2 by the growing mass of the animals in the herd. The time course of the body mass of growing-fattening pigs behaves like a saw-tooth wave, with one fattening period of 118 days. These growth periods are superimposed and interact with the time course of the outdoor temperature. To create statistically valid results that account of accidentally high or low stocking densities during heat stress events, we calculated the body mass based on a Monte Carlo method, called inverse transform sampling, a useful method for environmental sciences [e.g. 42,43]. Details of the method can be found in Mikovits, Zollitsch, Hörtenhuber, Baumgartner, Niebuhr, Piringer, Anders, Andre, Hennig-Pauka, Schönhart and Schauberger [9].

The model calculations were performed for the entire growing-fattening period for a body mass between 30 and 120 kg. The investigation period covered the years from 1981 to 2017.

2.3 Heat stress indices

Two parameters quantify the HS for farm animals: (1) the (dry bulb) air temperature T and (2) the temperature-humidity index $THI = 0.72\,T + 0.72\,T_{WB} + 40.6$ with the dry bulb temperature T and the wet bulb temperature T_{WB} . For a certain threshold X, the exceedance frequency P_X and the intensity of HS A_X, using the aggregated values between X and the time course of the HS index (i.e. the area under the time course), were calculated. P_X gives the number of hours during which the selected threshold is exceeded, whereas A_X includes the differences of the instantaneous values and the threshold. The following two threshold values were selected for fattening pigs: for the temperature X = 25°C and for the THI $X = 75$, which presents an alert situation of the thermal environment [11]. These two thresholds result in four HS indices P_{T25}, A_{T25}, P_{THI75}, and A_{THI75}. The HS indices were further processed as annual sums.

These four indices were calculated from the indoor parameters based on a simulation of the thermal environment inside the livestock building, where the vector of I_{INT} denotes for P_{T25}, A_{T25}, P_{THI75}, and A_{THI75} inside the building, and from the outdoor parameters, using meteorological measurements, easily available from a nearby weather station, where the vector I_{EXT} denotes for P_{T25}, A_{T25}, P_{THI75}, and A_{THI75}.

To estimate the likelihood of the occurrence of a certain HS index for a certain year t, a simple model was fitted by the dataset. The model is characterised by the expected value I_t of a HS index of a certain year t and the variability s^2. The expected value I_t is calculated by a linear regression of the logarithmically transformed HS index according to $\log I_t = k\,t + d$. The deviation of the HS indices from the linear trend I_t results in the variance s^2. The detrended (and logarithmically transformed) HS indices, according to $\Delta_{EXT,t} = \log T_t - \log I_{EXT,t}$ (deviation from the trend) were fitted to the Weibull, the Gumbel, and the Gauss (normal) distribution. The quality of the fit was determined by the Akaike information criterion AIC.

2.4 Statistical analysis

The observed trends of the HS indices [9] were tested by the signal-to-noise ratio SNR and the Mann-Kendall Trend Test. The signal-to-noise ratio SNR was calculated using the linear trend over 37 years and the standard deviation of the annual mean values of the HS indices. Under the assumption, that the SNR is distributed with the standard normal distribution $\mathcal{N}(0; 1)$, limits for the SNR and the p-values are as follows [44]: low significance $1.645 < SNR \leq 1.960$ ($0.05 < p \leq 0.10$), medium significance $1.690 < SNR \leq 2.576$ ($0.01 < p \leq 0.05$), and high significance $SNR > 2.576$ ($p \leq 0.01$). The second test for the trend of the HS indices was the rank-based nonparametric Mann-Kendall Trend Test with the test statistics τ and a one-sided test for an increasing temporal trend using the R package Trend.

The fitting of the selected distribution functions was performed by a maximum likelihood estimation, the goodness of the fit was evaluated by the Akaike information criteria AIC.

The variability of the HS indices Δ_{EXT} were tested by the Breusch-Pagan test for heteroskedasticity assuming that the residuals Δ_{EXT} are normally distributed. Using a χ^2 test, it is tested whether the variance of the errors from the regression depends on the values of the independent variable, the time t.

The relationship between the two sets of HS indices (I_{INT} and I_{EXT}) was investigated by a linear regression analysis, using the model calculations by Mikovits, Zollitsch, Hörtenhuber, Baumgartner, Niebuhr, Piringer, Anders, Andre, Hennig-Pauka, Schönhart and Schauberger [9] for I_{INT} and the corresponding meteorological Input data for I_{EXT}.

2.5 Economic impact function

The economic impact assessment is based on the reduction of the gross margin as a function of HS, estimated by the growing-fattening pig model of St-Pierre, Cobanov and Schnitkey [10]. The reduction of the gross margin is calculated by three parameters on an annual basis for one animal place: the reduction of body mass at the end of the fattening period (kg a^{-1}) (revenue), the reduction of dry matter intake (kg a^{-1}) (variable costs) and the increase of the mortality (%) (revenue). These three parameters were updated by data for 2020 from the Federal Institute of Agricultural Economics (AWI http://www.awi.bmnt.gv.at/) for feed with 0.25 € kg^{-1}, the revenue for a fattening pig with 1.7 € kg^{-1}, and the cost of a slaughtered pig (75 kg) with 100 € kg^{-1}. The original predictor of the impact function of St-Pierre, Cobanov and Schnitkey [10] is the area under the curve A_X for a THI threshold of $X = 72$. By the dataset of the HS index using the two THI thresholds, $X = 72$ (growing-fattening pigs) and $X = 74$ (sows), the impact function could be derived for the THI threshold $X = 75$ used in this paper. The economic impact function IMP due to HS reads as follows: $IMP = 0.0016\ A_{THI75}$ (Fig. 1).

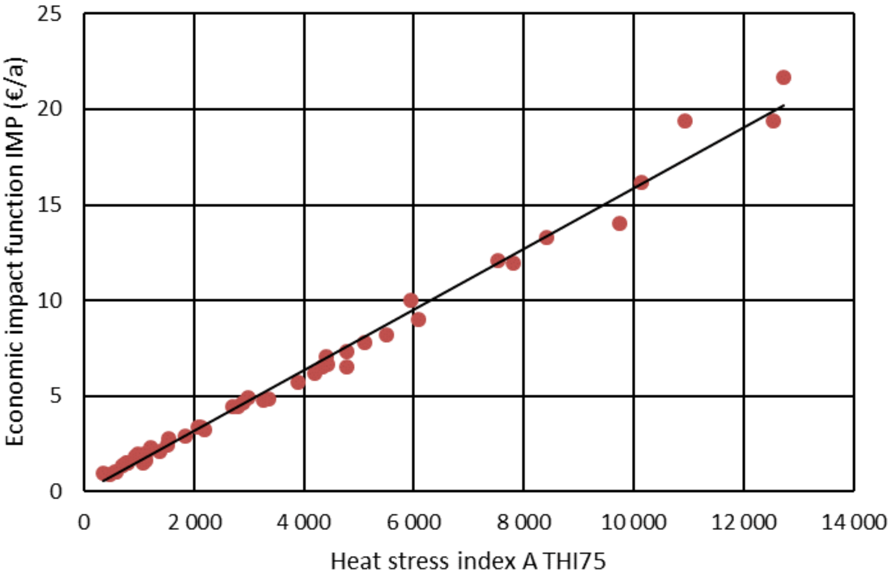

Fig. 1 Economic impact function IMP, described by the reduction of the gross margin per animal place as a function of the heat stress index A_{THI75} derived from St-Pierre, Cobanov and Schnitkey [10] with $IMP = 0.0016\ A_{THI75}$

3. Results

3.1 Relationship between indoor-related and weather-related heat stress indices

To assess the risk caused by HS inside confined livestock buildings, indoor parameters like air temperature and the temperature-humidity index THI should be the first choice. The disadvantage in using these parameters are the complex dependencies between indoor and outdoor (meteorological) parameters due to the thermal properties of the building, the ventilation system and its interaction with the livestock, which leads to intricate mathematical models associated with long computing times. The relationship between HS indices I_{INT}, calculated by indoor parameters, and the HS indices I_{EXT}, calculated by the outdoor (meteorological) parameters, shows a high linear correlation. The statistical parameters of the linear regression are summarised in Tab. 2 and graphically presented in Fig. 2. All HS indices I_{EXT} show a high explanatory power for the indoor-related indices I_{INT}. I_{EXT} explain more than 80% of the variance ($r^2 > 0.80$) in any case. The intercept of the regression can be interpreted as the impact resulting from an increase of the indoor temperature and indoor humidity by the sensible and latent heat release of the farm animals. The slope of the two exceedance frequencies P_{T25} and P_{THI75} are closer to the line of identity (1:1) compared to the HS intensity A_{T25} and A_{THI75}.

Tab. 2 Linear regression results of I_{INT} (calculated by the indoor parameters) as a function of I_{EXT} (calculated by weather data)

Heat stress index I_{INT}	Coefficient of determination adjusted r^2	Linear regression $I_{INT} = k\, I_{EXT} + d$
P_{T25} (h/a)	0.8354	= 1.166 P_{T25} + 405.0
A_{T25} (Kh/a)	0.9084	= 1.505 A_{T25} + 1219.7
P_{THI75} (h/a)	0.8032	= 1.495 P_{THI75} + 212.9
A_{THI75} (h/a)	0.8862	= 2.130 A_{THI75} + 489.9

Due to the reliable linear relationship between the two sets of HS indices, shown by the high coefficient of determination ($r^2 > 0.80$) (Tab. 2), HS indices I_{EXT} can be used as a proxy to quantify the HS impact on farm animals without the need of a determination of the indoor parameters. This is an advantage for manageability, e.g., for a weather-index based insurance because the meteorological parameters are easily available from national weather services and no further model calculations are required.

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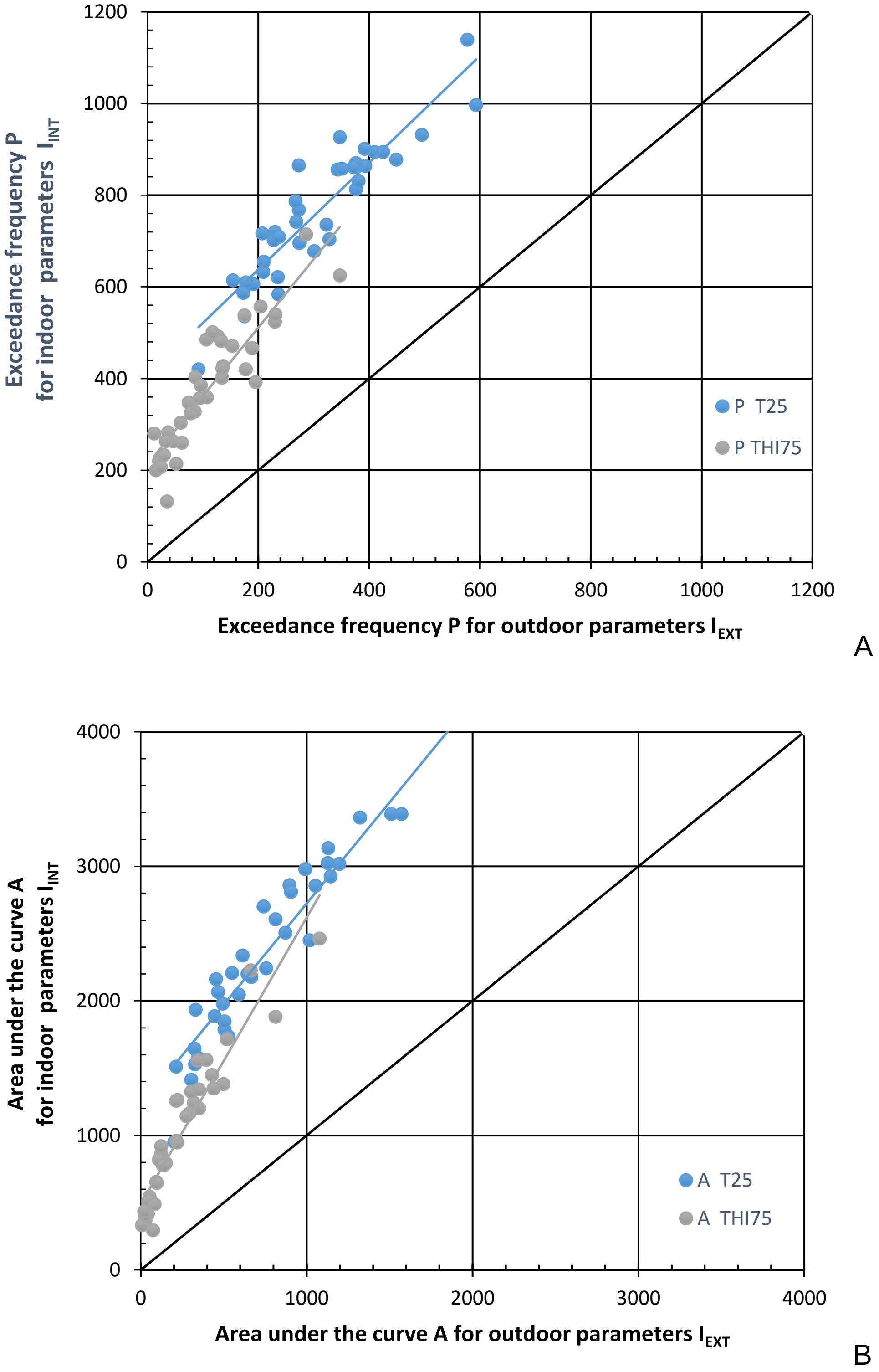

Fig. 2 Relationship between the weather-related heat stress indices I_{EXT} and indoor-related indices I_{INT}. The exceedance frequencies (h/a) of a threshold Px are presented in panel A, the heat stress intensities (area under the curve for a threshold) Ax in panel B. The parameters of the linear regression are summarised in Tab. 2.

3.2 Consequence of global warming on the likelihood of heat stress indices

The temporal trend of the weather-related HS indices I_{EXT} could be confirmed by the signal-to-noise ratio SNR and the Mann-Kendall trend test on a high level of significance with $p < 0.04$ and $p < 0.001$, respectively (Tab. 3).

Tab. 3 Statistical analysis of the temporal trend of the weather-related heat stress indices I_{EXT} by the signal-to-noise ratio SNR and the Mann-Kendall Trend Test with the test statistics τ with the corresponding p-values.

Weather-related heat stress indices I_{EXT}	**Signal-Noise Ratio**		**Mann-Kendall Trend Test**	
	SNR	p	τ	p
P_{T25}	2.001	0.023	0.4271	< 0.001
A_{T25}	1.790	0.037	0.3982	< 0.001
P_{THI75}	2.071	0.019	0.4174	< 0.001
A_{THI75}	1.832	0.033	0.3832	< 0.001

The simple model to estimate the expected likelihood of the occurrence of the HS indices I_{EXT} for a certain year t were fitted by the empirical data to determine the expected value I_t and the variability s^2. The expected value I_t of the distribution and the statistical parameters of the linear trend are given in Tab. 4. The results of all four weather-related HS indices I_{EXT} show a high significance with $p < 0.001$ and a coefficient of determination r^2 between 30% and 33%.

Tab. 4 Temporal trend of the weather-related heat stress indices $\log I_t = k\, t + d$, calculated by the logarithmically transformed heat stress indices $\log I_{EXT}$ with the slope k, the intercept d, the coefficient of determination r^2, and the p value.

Weather-related heat stress indices I_{EXT}	**Linear Regression of the temporal trend $\log I_t$**			
	Trend k	**Intercept d**	**Coef Det r^2**	**p**
P_{T25}	0.009326	-16.187	0.333	< 0.001
A_{T25}	0.013745	-24.643	0.314	< 0.001
P_{THI75}	0.019806	-37.658	0.334	< 0.001
A_{THI75}	0.025600	-48.987	0.296	< 0.001

The deviation of the HS indices from the linear trend results in the variance s^2 showing a homoscedasticity of the four detrended HS indices Δ_{EXT} , which could be confirmed by the Breusch-Pagan test for all four weather-related HS indices I_{EXT}= [P_{T25}, A_{T25}, P_{THI75}, A_{THI75}] on the 5% level. The detrended (and logarithmically transformed) HS indices were fitted to the Weibull, the Gumbel distribution, and the Gauss (normal) distribution. The last distribution shows the best overall fit, assessed by the Akaike information criterion AIC. In Tab. 5, the standard deviation s and the AIC are summarised. Fig. 3 compares the empirically detrended (and logarithmically transformed) HS indices Δ_{EXT} with the three fitted CDFs: Gauss, Weibull, and Gumbel distribution. Especially the right tail of the detrended HS indices Δ_{EXT} is fitted well by the normal distribution.

Tab. 5 Standard deviation s of the detrended (and logarithmically transformed) weather-related heat stress indices Δ_{EXT} and the Akaike information criteria AIC.

Weather-related heat stress indices Δ_{EXT}	**Standard deviation s**	**AIC**
P_{T25}	0.1354	-38.98
A_{T25}	0.2075	-7.36
P_{THI75}	0.2867	16.54
A_{THI75}	0.4024	41.64

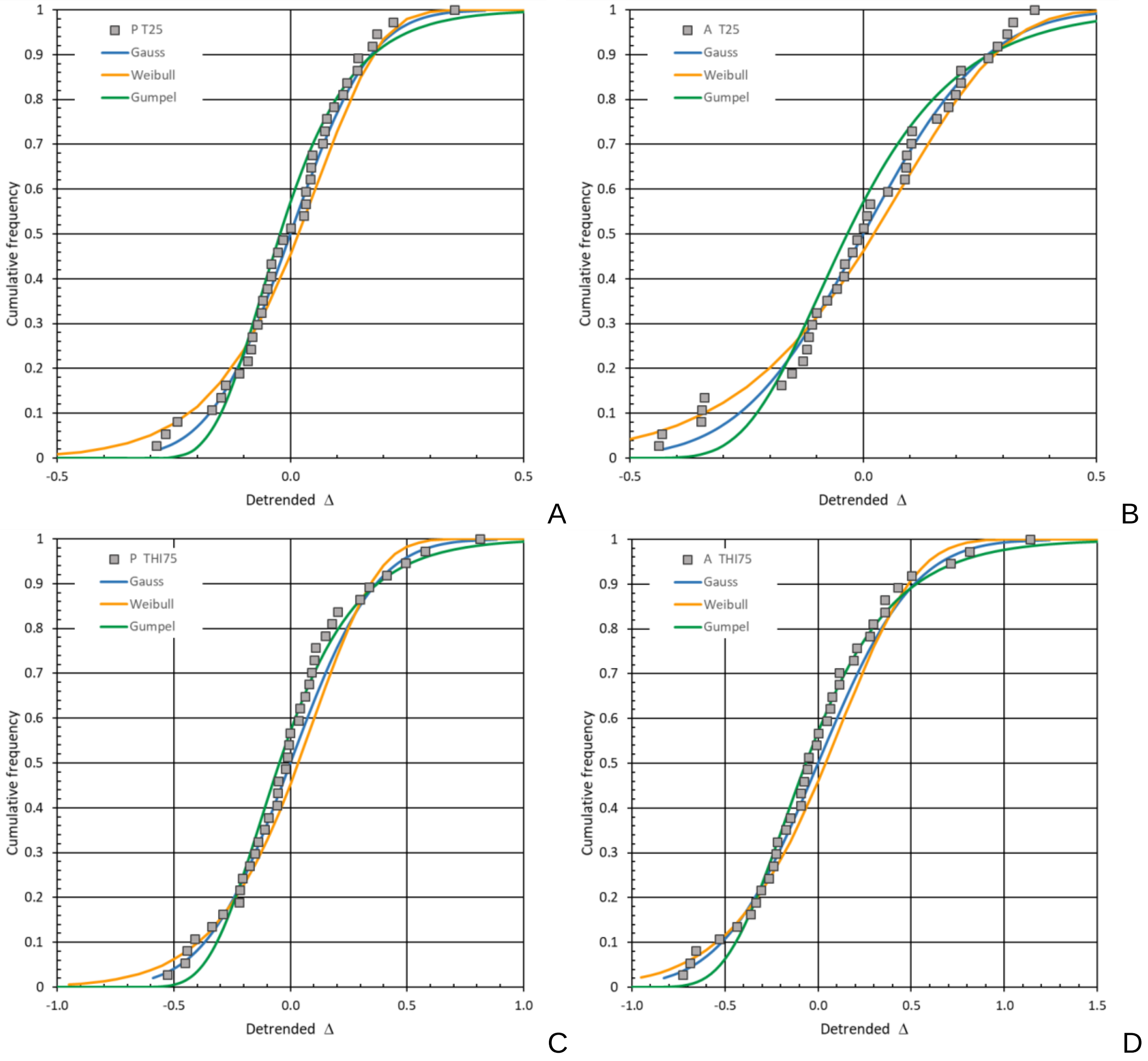

Fig. 3 Cumulative distribution of the detrended (and logarithmically transformed) heat stress indices Δ_{EXT} and three cumulative distribution functions: Gauss, Weibull, and Gumbel distribution for the four weather-related heat stress indices P_{T25} (A), A_{T25} (B), P_{THI75} (C), and A_{THI75} (D).

These parsimonious models for the four HS indices I_{EXT} were used to determine the likelihood of their occurrence in a certain year t. In Fig. 4 the likelihood for the past (t = 1980 and t = 2020) in panel A and for the near future (t = 2030) in panel B are shown, using the cumulative distribution function CDF of the log-normal distributions of P_{T25}, A_{T25}, P_{THI75}, and A_{THI75}.

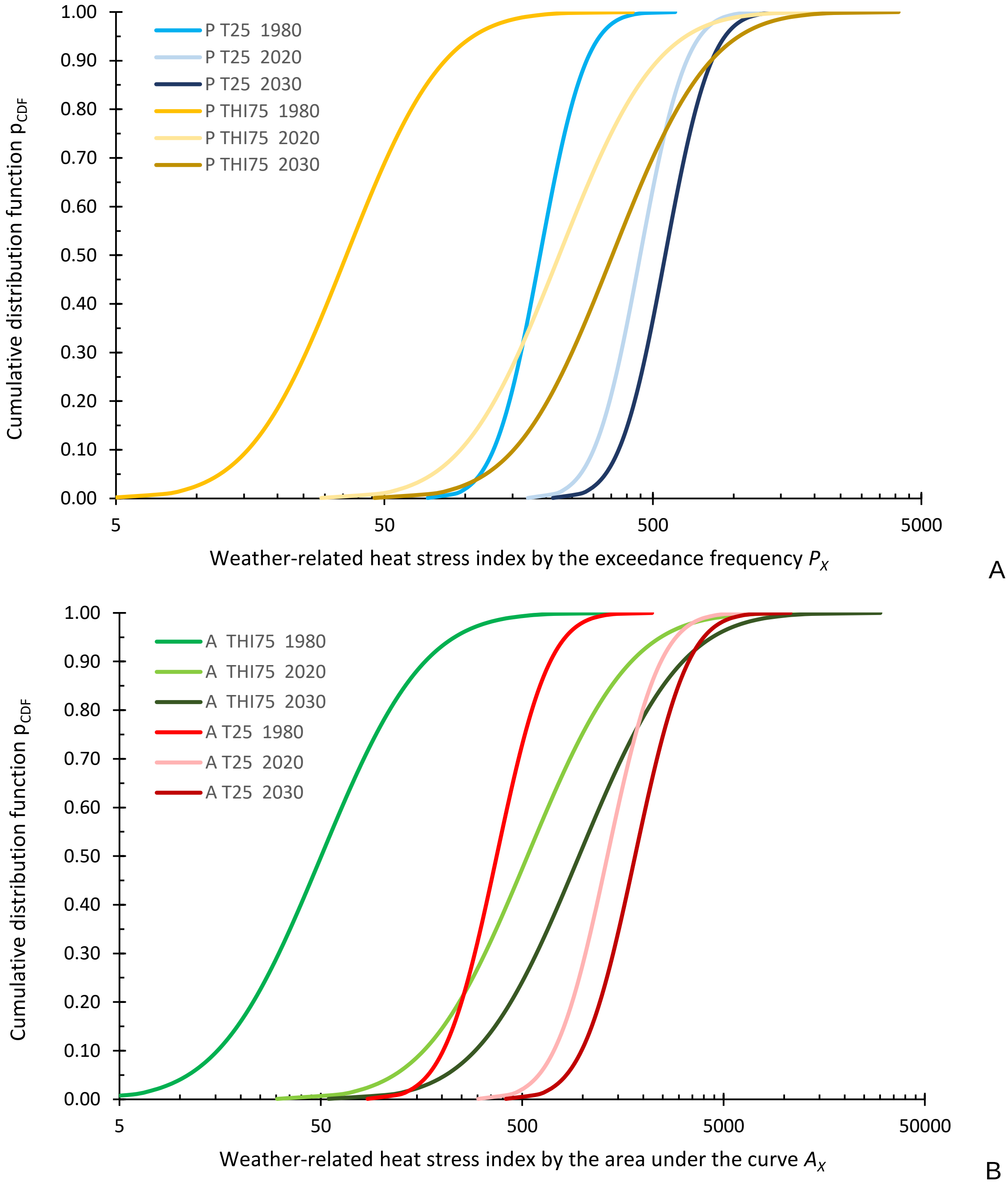

Fig. 4 Likelihood for the occurrence of the weather-related heat stress indices I_{EXT} = [P_{T25}, A_{T25}, P_{THI75}, A_{THI75}] shown by the cumulative distribution function CDF of a log-normal distribution for t = 1980 (dark colour), t = 2020 (light colour), and t = 2030 (very dark colour) for the exceedance frequency P_X (panel A) and the area under the curve A_X (panel B)

3.3 Consequence of global warming on extreme values of heat stress indices

For the economic risks the temporal change of the likelihood of extreme values (right tail values of the curves in Fig. 4) is an important aspect. For this analysis, we defined the extreme value by the 90-percentile (which corresponds to an exceedance probability P_E of 10% and a return period of 10 years).

The extreme value $E_{t,10\%}$ of each weather-related HS index was determined by the cumulative distribution function shown in Fig. 4 for the year t = 1980 with $E_{1980,10\%}$ and for t = 2020 with $E_{2020,10\%}$ and by the 90-percentile of the CDF.

Based on the exceedance probability P_E = 10% the corresponding return period RP = 1/ P_E results in RP = 10 a (1-in10-years event), as the length of an average time interval between the occurrences of two years with a HS level that exceeds the extreme value $E_{t,10\%}$.

For the time shift from 1980 to 2020 and for the near future from 2020 to 2030, the corresponding exceedance probability for t = 2020 and t = 2030 with $P_{E,2020}$ and $P_{E,2030}$ was calculated according to

$$P_{E\,t} = \frac{1}{2}\left[1 - \operatorname{erf}\left(\frac{log\left(E_{2020,10\%}\right) - \log I_t}{s\sqrt{2}}\right)\right]$$

with the temporal trend I_t (Tab. 4) and the standard deviation of the detrended values s (Tab. 5). The return period RP (in years) and the exceedance probability $P_{E,t}$ are presented for the time shift in the past and for the time shift in the future in Tab. 6.

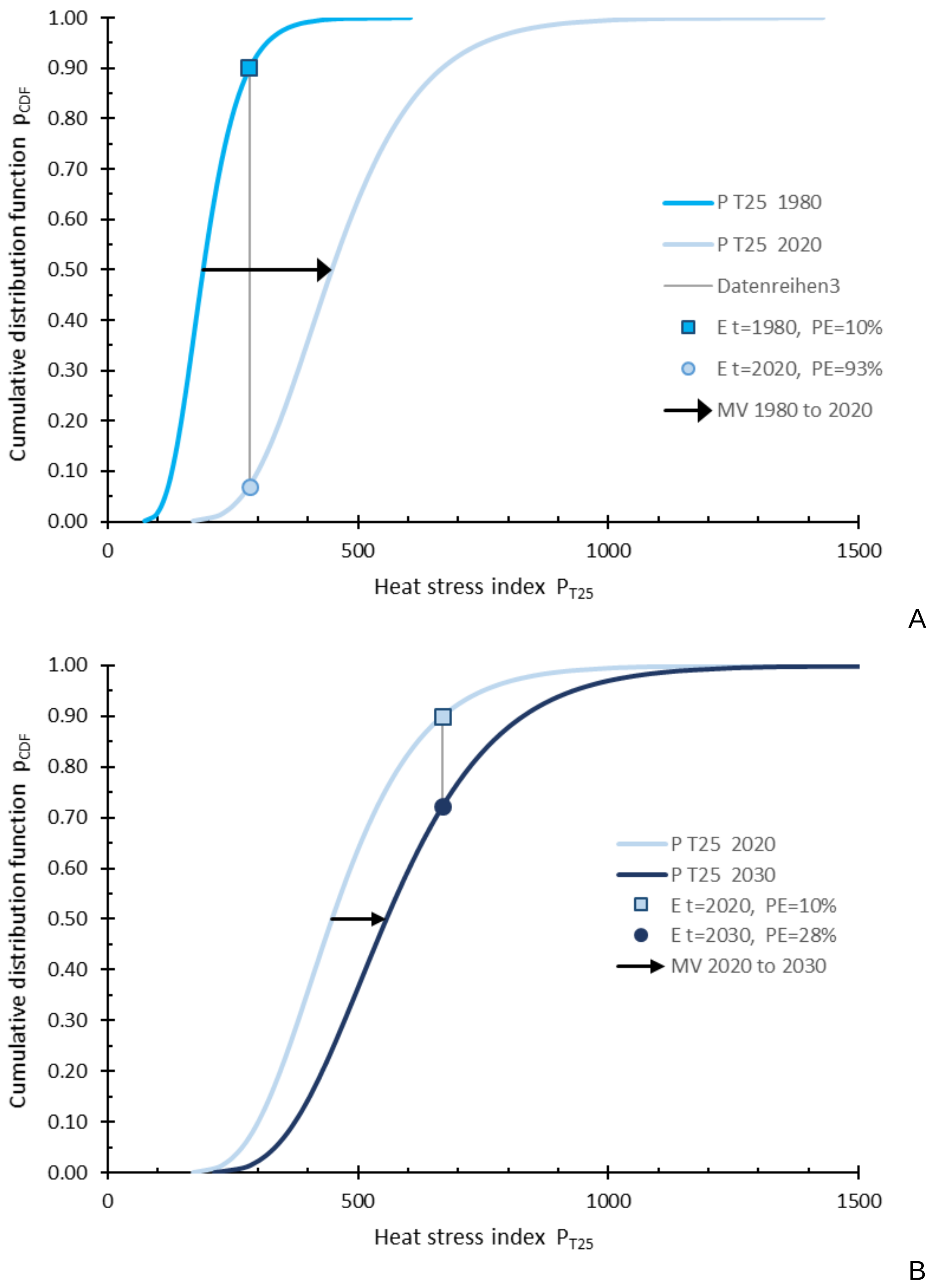

Fig. 5 The cumulative distribution function showing the likelihood of the occurrence of P_{T25}. The shift of the mean value ($p_{CDF} = 0.5$) is presented by the black arrow. In panel A the scenario of the past ($t = 1980$ and $t = 2020$), in panel B the scenario of the near future ($t = 2020$ and $t = 2030$) is shown.

For a weather-index based insurance, a certain percentile of the CDF in Fig. 5 (e.g. 95-percentile, which means a 20-year return period) can be selected as a threshold to decide if the risk transfer mechanism gets active and the insurance benefit is paid out.

Tab. 6 Exceedance probability P_E and return period RP using the 90-percentile p_{CDF} = 90% (P_E = 10%) of the cumulative distribution function. The time shift was calculated for the past t = 1980 and t = 2020 and the near future t = 2020 and t = 2030. The shift of the mean values MV shows the consequence of global warming.

Weather-related heat stress indices I_{EXT}	**Expected values for p =10% $E_{t,\,10\%}$**	**Exceedance probability P_E and return period RP**			
		P_E (%)	**RP (a)**	**Shift of the MV**	**Shift %**
Time shift from 1980 to 2020	$E_{1980,10\%}$	**for t = 2020**			
P_{T25} (h/a)	283	93.0	1.1	258	136
A_{T25} (Kh/a)	689	91.4	1.1	951	255
P_{THI75} (h/a)	84	93.1	1.1	188	520
A_{THI75} (h/a)	165	89.7	1.1	481	957
Time shift from 2020 to 2030	$E_{2020,10\%}$	**for t = 2030**			
P_{T25} (h/a)	668	27.7	3.6	107	24
A_{T25} (Kh/a)	2442	26.8	3.7	493	37
P_{THI75} (h/a)	520	27.7	3.6	129	58
A_{THI75} (h/a)	1742	25.9	3.9	427	80

For the four decades in the past (1980 to 2020) the return period was shortened from RP = 10 a in 1980 to about RP = 1 a, which means that the extreme value with an exceedance probability of 10% in 1980 can be expected every year in 2020. The mean values (MV) increased during the four decades between 136% (P_{T25}) and 957% (A_{THI75}). In Fig. 5A the scenario of the weather-related HS index P_{T25} is shown exemplarily for the past (t = 1980 and t = 2020). The exceedance probability P_E = 10% (p_{CDF} = 90%) in the year t = 1980 results in $E_{1980,10\%}$ = 283 h/a (Table 7). The corresponding exceedance probability 40 years later (t = 2020) is P_E = 93%. This means, that the extreme value of the year t = 1980 $E_{1980,10\%}$ = 283 h/a will be exceeded with a probability of 93% in 2020. The mean value was more than doubled from 190 h/a (in 1980) to 448 h/a 40 years later (Fig. 5A).

For the next decade (2020 to 2030) the return period will be shortened from RP = 10 a in 2020 to 3-4 years in 2030. An increase of about 24% (P_{T25}) to 80% (A_{THI75}) of the mean value in relation to 2020 can be expected for the upcoming decade. In Fig. 5B the likelihood of P_{T25} for the near future is shown. The exceedance probability P_E = 10% (p_{CDF} = 90%) in the year t = 2020 $E_{2020,10\%}$ = 668 h/a is shifted for the year t = 2030 to P_E = 28%. The mean value increases from 448 h/a to 556 h/a.

For both scenarios (past and near future), the increase of HS is much higher for the *THI* index (P_{THI75} and A_{THI75}) compared to the temperature index (P_{T25} and A_{T25}). This means, that not only the air temperature but also the humidity, which is part of the *THI* index, will increase with time. Otherwise, the temperature-based index would grow proportional to the *THI* index.

3.4 Economic risk for pig farms due to global warming

The economic risk due to global warming is assessed by the product of the likelihood of HS and the economic impact function. The economic impact function *IMP* describes the expected reduction of the gross margin as a function of the HS index A_{THI75}, shown in Fig. 1.

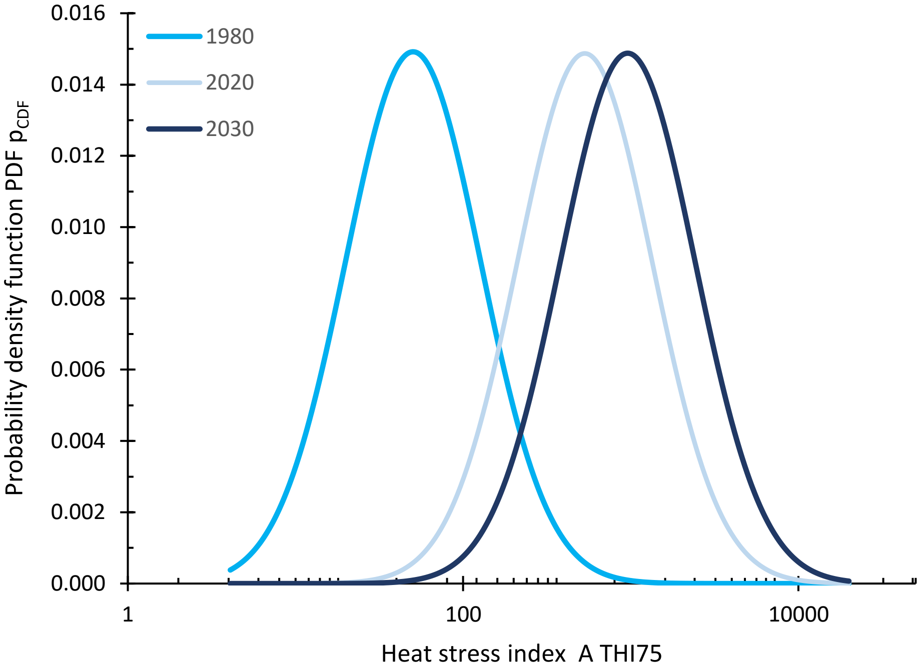

Fig. 6 Likelihood of the occurrence of the weather-related heat stress index A_{THI75} for t = 1980, t = 2020, and t = 2030

The likelihood of the weather-related HS index A_{THI75} is shown by the probability density function (PDF) in Fig. 6. It defines the temporal trend I_t which gives the expected value of the HS index for a certain year t (mean value (maximum) of the PDF) and the standard deviation s.

Tab. 7 Statistics of the economic risk by the reduction of the gross margin per animal place (€ a^{-1}) for t = 1980, t = 2020, and t = 2030

Year t	**Reduction of the gross margin due to global warming (€ a^{1}) per animal place**		
	Median	**90-Percentile (10 a return period)**	**95-Percentile (20 a return period)**
1980	0.08	0.27	0.38
2020	0.87	2.86	4.00
2030	1.57	5.13	7.18

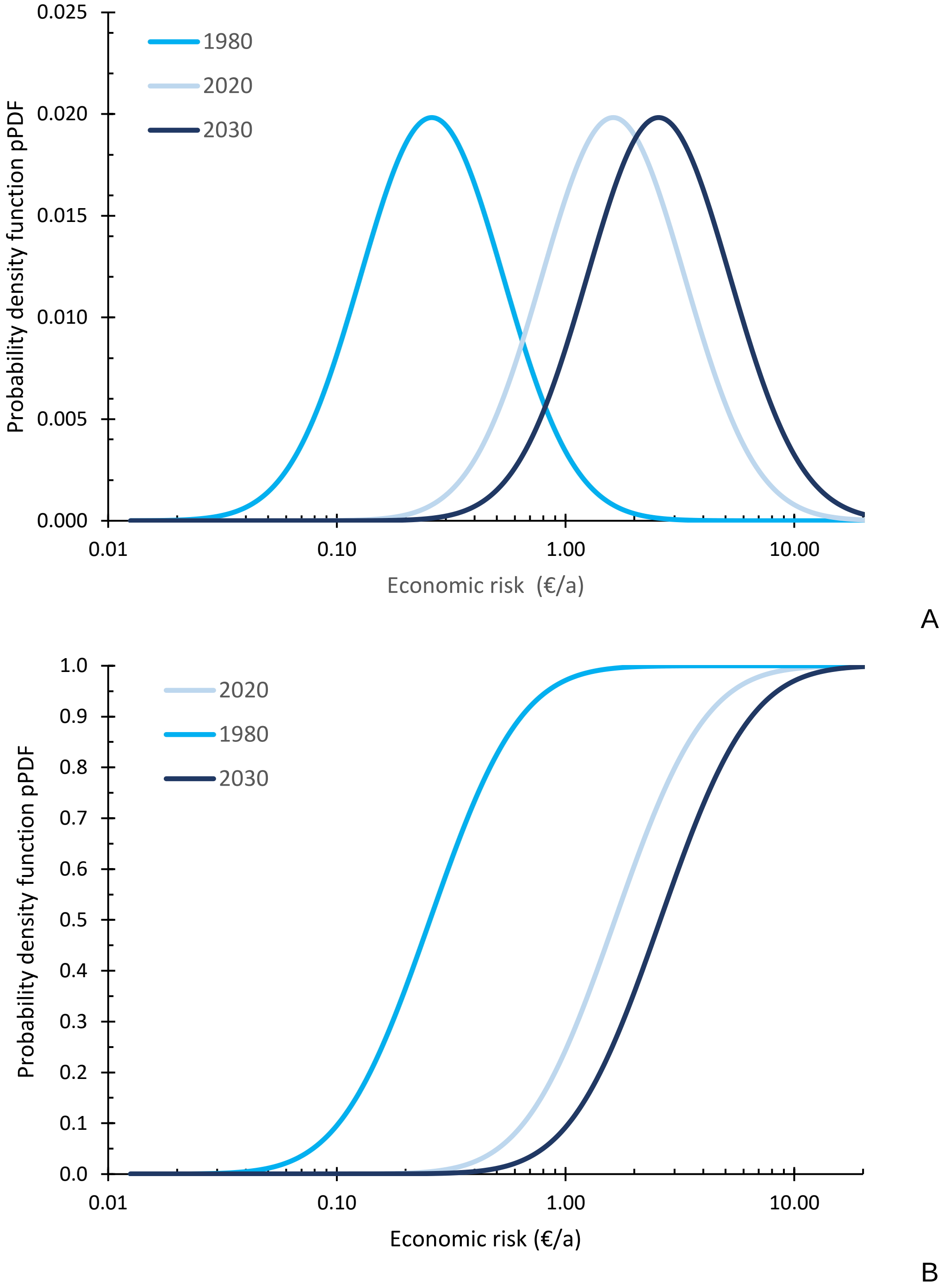

Fig. 7 Distribution of the economic risk by the reduction of the gross margin for t = 1980, t = 2020, and t = 2030 shown by probability density functions PDF (panel A) and cumulative distribution functions CDFs (panel B).

The economic risk due to global warming is shown by PDFs (Fig. 7a) and CDFs (Fig. 7b) for 1980, 2020, and 2030. The shape of the PDFs and the maximum slope of the CDFs are identical for all three years due to the constant variability s^2 of the detrended and logarithmically transformed HS index ΔA_{THI75} (Tab. 5). Due to the temporal trend of the HS indices (Tab. 4), the probability shifts from 1980 to 2030. The statistics of the reduction of the gross margin per animal place (i.e. ca. 3 pigs/a) due to HS is shown in Tab. 7. The median moves from 0.08 € a^{-1} to 1.57 € a^{-1}. For HS events with a probability of a return period of RP = 10 years, the economic risk grows from 0.27 € a^{-}

^{1} to 5.13 € a^{-1} per animal place. For a return period of 20 years, the economic risk is 0.38 € a^{-1} for 1980 and 7.18 € a^{-1} per animal place for 2030, which is a 20-fold increase.

4. Discussion

Farmers require information on the likelihood and severity of future climate extremes and their effects on farm animals to take well-founded management decisions. The temporal trend of an Austrian case study shows an increase of the frequency of four HS indices over the last four decades [9]. A significant time trend of the HS indices between 1981 and 2017 could be determined. The poor variance estimate for the trends determined by a regression analysis resulted in a poor estimate of the test statistics for the SNR, which resulted in an incorrect inference about the trend [45]. Therefore, the non-parametric Mann-Kendall test was applied as well. Della-Marta, Haylock, Luterbacher and Wanner [37] used a piecewise de-trending method for a much longer time series (since 1880) which was not useful for a time series of 37 years. As a distribution function, a normal distribution was selected, which fits the empirical right tail values. A detailed review of appropriate distribution functions and methods to analyse the time trend can be found in Visser and Petersen [46]. Since we used a 20-year and a 10-year return period, the selected PDFs and the corresponding shapes of the right tails are not as sensitive as for longer return periods [46,47]. The goodness of the fit of the empirical data from the detrended and logarithmically transformed HS indices Δ_{EXT} with a Gaussian distribution was demonstrated by the low values of the AIC and graphically shown in Fig. 3. Especially the right tail is fitted well by the selected normal distribution.

The Expert Team on Climate Change Detection and Indices (ETCCDI) has defined a set of so-called climate indices that describe different fields of climatic change [48]. Such climate indices are the mean number of summer days (maximum temperature above 25°C), heat days (maximum temperature above 30°C), or tropical nights (minimum temperature above 20°C) per year. They are strongly connected to the indoor climate of confined livestock buildings. Klein Tank and Können [49] investigated meteorological stations in Central Europe and found that the number of summer days increased by about 2-4 days per decade in the time period from 1946 to 1999. Compared to this, the mean number of summer days per year in the case study region of Wels was 42.3 in the period 1971 - 2000. The number increased by about 6 days on average to 48.8 in the period 1981-2010. Depending on different possible future climate change signals, this number could increase to values from 53.5 up to 62.7 until the middle of this century in the period 2036 - 2065. The heat days occur less frequently in this area. In the period 1971 – 2000, a mean number of 5.1 heat days per year was observed, whereas in the period 1981 – 2010, this number increased to 7.9 days on average. Especially tropical nights have a big influence on the health of the human population, especially in the case of several of such days in a row [50]. This effect can be expected for farm animals to an even greater extent. Sillmann and Roeckner [51] expected that tropical nights will increase in Central Europe by about 10–25 days on average between today and the end of the 21st century.

HS indices can be calculated by weather-related parameters from a meteorological station, by measured data, or by simulated data of indoor parameters [9,30,31]. The investigated relationship between HS indices, which are calculated by the indoor parameters and those calculated by meteorological parameters, show a coefficient of determination above 80% and a slope of the linear regression between 1.17 and 2.13 which means, that the indoor parameters are more sensitive to HS [17]. Nevertheless, the weather-related HS indices can be used as a reliable proxy for the indoor indices. However, the indoor simulation describes the thermal environment of animals inside a confined livestock building in a more precise way. Its disadvantages are the resource demand to determine the system parameters of the building (e.g. U value of the construction elements), the ventilation system (maximum and minimum ventilation rate, and key parameters of the control unit), and the livestock as a source of sensible and latent energy. Weather-related HS indices have the advantage of easily accessible input parameters provided by meteorological stations. E.g. in Austria, about 270 stations with a mean distance of about 11 km provide data in a temporal resolution of one hour. This means that a representative meteorological station can be expected in the vicinity of a livestock building. The HS indices, calculated from meteorological data, could be published on a day-to-day basis, similar to other agro-meteorological services, such as indices like the growing degree days for plants [52-54].

Several adaptation measures are in use to alleviate heat stress and to improve the thermal environment of the animals kept inside livestock buildings [17,21]. Most of these measures require investments and increase running costs. To strengthen the economic resilience of livestock farms and to allow for deliberate investment decisions, the economic risks should be estimated and managed. This article quantified the likelihood of HS for farm animals in 1980, 2020 and in 2030. Subsequently, the economic risk was assessed by the product of the HS likelihood and the economic impact. The latter is expressed as losses in gross margins for growing-fattening pigs as a function of the A_{THI75} heat stress index. The predictor of the cost function in St-Pierre, Cobanov and Schnitkey [10] is the HS index calculated by the THI and the threshold of X_{THI} = 75. The variability of this HS index is caused by differences in local climates across the entire USA (spatial variability), whereas the variability of the HS indices presented here is caused by the trend due to global warming. The assessment of the economic impact following the approach of St-Pierre, Cobanov and Schnitkey [10] includes the reduction of the animals' live mass at the end of the fattening period, the related reduction of feed required and the increased mortality of the animals. These traits are parameterised by linear functions. It is however not plausible that the impact of HS will be the same for the temperature range of 25°C to 28°C and for 30°C to 33°C. This fact was investigated by several authors [15,55,56]. In a European study about risk factors for mortality in fattening pigs, a significant seasonal impact with higher mortalities of pigs placed at the end of the year was found, which was associated with infectious diseases [57]. This finding is in contrast to a higher mortality in summer in the Midwest in the USA [58], which might be associated with a higher frequency of HS in this region. To the authors' knowledge, no evaluation of mortality in fatteners during extreme weather periods has been performed so far. For this reason, the economic assessment of the impact of heat stress is mainly based on the decrease in livestock growth parameters. Other variable costs such as the market driven costs for piglets, veterinary services, energy for the ventilation system, and water consumption were not taken into account in this study, despite the effect of HS on these [9].

Another limitation results from impact on livestock well being, which declines from heatstress and can impact consumer's willingness to pay for pork. Similarly, pork quality may decline. For example, an alteration of carcass composition and an increase in the risk of occurrence of pale, soft, exudative (PSE) meat in pigs can be expected [59,60] and may reduce the revenue. In pigs, decreased carcass quality as the consequence of heat stress is reflected by pork processing problems due to a more flimsy adipose tissue and in general increased lipid and decreased protein content [10,61]. Above the pig's thermal neutral zone, nutrient energy sources are shifted from synthesis of products to maintenance of body homeostasis by heat release. On the other hand, heat stress can lead to a higher efficiency in conversion of dietary energy into body mass. Carcass tissue gain might be improved, while carcass composition and quality may be impaired [61,62]. In fattening pigs an interaction of housing at 32°C and limited space (0.66 m² per pig) was found to be connected with an increased adipose iodine value and a decreased saturated:unsaturated fatty acids ratio. Pigs kept at higher temperature showed changes in carcass lipid and bacon quality, e.g. lean:fat ratio of bacon slices and increased quantity of collagen in belly fat [63].

Acute or chronic heat stress prior to slaughter can alter the chemical properties of pork by inadequate pH lower or higher than 5.6 - 5.7 within 3 - 5 hours after slaughter. Under situations of increased temperature and metabolism prior to and during slaughter, lactic acid cell levels increase resulting in low pH, which damages muscle proteins followed by a high dripping loss (poor water holding capacity), colour- and flavourless after cooking (PSE). In case of long-term stressors no glycogen is available to be converted into lactic acid post-mortem, resulting in a high pH value and dry meat, which can spoil rapidly (DFD). In general, heat stress was found to reduce food safety due to increased bacterial growth and shedding [60]. This means that the economic impact function based on the assumptions of St-Pierre, Cobanov and Schnitkey [10] likely underestimates the total costs for farmers caused by HS. An analysis of greenhouse gas and air pollutant emissions from pig production systems driven by climate change, which was based on the same data and indoor climate models, showed that emissions increase with climate change for the entire production chain from breeding to finishing [64,65]. Hence, the (externalised) climate- and environmental-related costs for the society will also increase. In case of an internalisation of external costs (e.g. with a tax on emissions) due to climate change, economic losses of pig production systems could further increase. Its effect depends on the competitiveness of markets, i.e. whether consumers take a share as well. Consequently, both the private and social costs form livestock production likely will increase with climate change.

Hansen, *et al.* [66] pointed out that insurances, conservation soil management, genetically adapted feed crops and diversified farming systems are the most important factors increasing resilience against climate change. The development of insurances in the livestock sector is generally lower than in the crop sector. Only a few insurance products for livestock are offered, predominantly for animals kept on pasture in developing countries and for sanitary assistance programs for severe diseases. Livestock risk management relies predominantly on sanitary assistance programs for major crises (diseases with high externalities), which are often subsidised by the public [67]. Weather-index based insurance is a relatively new tool that is helpful for farmers in managing risks. It pays out, based on an index, such as the HS index, calculated by meteorological data from a local weather station, rather than based on a consequence of weather, such as a reduction of the average daily gain or the mortality of the livestock. Most of the weather-index based insurances are configurated to the grassland keeping of animals, the impact of the availability of feed, mostly for extensive livestock production in India [68], Iran [69,70], Ethiopia [71,72], South Africa [73], and for tropical areas [74].

Since livestock production shows a high vulnerability caused by a relative scarcity of equity capital, the risk transfer by means of weather derivatives or insurance could be attractive for farmers. Even the European Union [75] and COP21 leaders in 2015 [69] asked for risk management to assist farmers in addressing the most common risks, setting up mutual funds, and the compensation paid by such funds to farmers for losses suffered as a result of adverse climatic events. It is not only rentability but also stability and liquidity of farms which may be negatively influenced by HS and insurances may help to alleviate these effects.

Especially for weather-index based insurance as one option for farm risk management, the relevant indices have to be calculated from meteorological data to achieve an objective measure. Following the methodology for HS indices presented in this article, administrative costs and moral hazards can be minimised and allow companies to offer simple, affordable and transparent risk transfer [68]. Such indices describing drought, flooding or the occurrence of diseases, are highly correlated to local yields [52,76].

For intensive livestock production in confined houses, the economic risk by HS can be reflected in considerable monetary losses. Risk transfer mechanisms against HS related economic losses will very often compete with adaptation measures in confined livestock buildings such as energy-saving air treatment systems, which cool the inlet air (e.g. cooling pads, earth-air-heat exchanger), 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) [21,77]. The use of such adaptation measures could be supported through discounted premiums [78].

5. Conclusions

The assessment of the economic risk due to global warming and the related HS on livestock kept inside confined buildings suggests a multistage process. (1) The temporal trend of meteorological parameters describing the environment of the livestock building was analysed. It was shown that routinely measured air temperature and humidity data can be applied to assess the chosen HS indices. This approach is more feasible and straightforward as the determination of indoor parameters. The measured meteorological parameters drive the indoor climate of such buildings. (2) The likelihood of heatstress was estimated. Climate change leads to an unfavourable increasing trend of chosen weather-related HS indices. Beside an estimator of the expected value of an HS index, the uncertainty was assessed as well. This was demonstrated especially when investigating the consequence of of global warming on the extreme values of the HS indices. The most relevant right tail of the detrended HS indices is fitted well by the normal distribution (Fig. 3). Likelihood and exceedance probability for the occurrence of a certain weather-related HS index increased considerably during the last 40 years and will continue to increase in the near future (Figs. 4 and 5). Correspondingly, the return period for extreme values decreased from 10 years in 1980 to 1 year in 2020 (Table 7); even this trend is predicted to continue. (3) The impact of increased HS on the animals will cause a reduction of their performance. This depression was quantified as loss of gross margins. To quantify the economic impact of increasing HS, three parameters, i.e. reduction of body mass at the end of the fattening period, dry matter intake, and the increase of the mortality, were taken into account. (4) In the last step, the HS events assuming a probability of a return period of 10 years results in a growth of the economic risk from 0.27 € a^{-1} to 5.13 € a^{-1} per animal place, which is around 5% of gross margins for a typical farm. For farmers such a risk assessment is an essential tool for management decisions like the implementation of adaption measures to reduce HS, thermotolerant and adapted breeds, or feeding strategies by adjusting diet composition.

The insurance sector is likely to become more relevant for future adaptation decisions, mostly based on weather-index based schemes, weather derivatives, or catastrophe bonds [78]. Weather-index based insurance is a relatively new but innovative approach to insurance provision that pays out benefits based on a predetermined index for loss of assets and investments (reduction of animal performance, mortality etc.). Because an index based insurance does not necessarily require traditional services of insurance claim assessors, it allows a quicker and more objective process of claims settlement [68].

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