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Review: Challenges for dairy cow production systems arising from climate changes

M. Gauly[1†] and S. Ammer[2]

[1]Faculty of Science and Technology, Livestock Production Systems, Free University of Bolzano, Universitätsplatz 5, 39100 Bolzano, Italy; [2]Division of Livestock Production Systems, Department of Animal Sciences, University of Göttingen, Albrecht-Thaer-Weg 3, 37075 Göttingen, Germany

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The so-called global change refers to changes on a planetary scale. The term encompasses various issues like resource use, energy development, population growth, land use and land cover, carbon and nitrogen cycle, pollution and health, and climate change. The paper deals with challenges for dairy cattle production systems in Europe arising from climate change as one part of global changes. Global warming is increasing, and therefore ecosystems, plant and animal biodiversity, and food security and safety are at risk. It is already accepted knowledge that the direct and indirect effects of global warming in combination with an increasing frequency of weather extremes are a serious issue for livestock production, even in moderate climate zones like Central Europe. The potential and already-measurable effects of climate change (including increase in temperature, frequency of hot days and heat waves), in particular the challenges on grassland production, fodder quality, nutrition in general, cow welfare, health as well as performance of dairy production, will be reviewed. Indirect and direct effects on animals are correlated with their performance. There are clear indications that with selection for high-yielding animals the sensitivity to climate changes increases. Cumulative effects (e.g. higher temperature plus increased pathogen and their vectors loads) do strengthen these impacts. To cope with the consequences several possible adaptation and mitigation strategies must be established on different levels. This includes changes in the production systems (e.g. management, barn, feeding), breeding strategies and health management.

Keywords: climatic conditions, global warming, cattle, milk production, adaptation

Implications

The effects of climate change on livestock will be the consequence of combined changes of air temperature, precipitation, frequency and magnitude of extreme weather events. They include both direct and indirect effects. Climate change increase the overall need of adaptation and mitigation strategies covering available tools from management, nutrition, health as well as plant and animal breeding. Predicted changes will impose selection pressures on traits important for biological fitness (and production). Genetic adaptation is important for the future of livestock systems, especially high-yielding animals. Changes will come along with costs to producers and consumers.

Introduction

Even for rather moderate climate zones as Central Europe, predictions for future climatic conditions, particularly summer months, implicate increasing frequencies of heat periods and droughts. In the north of Germany, a region of dairy production and characterized by temperate oceanic climate, the precipitation is expected to be lowered by 15% in summer months, and the annual mean ambient temperature is expected to rise by 2°C up to the year 2050. It is also expected that the number of hot days (above 30°C) will slightly increase (Gauly *et al.*, 2013). According the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (**IPCC**) global average surface temperature will increase in the range of 0.3°C to 4.8°C by the year 2100 (IPCC, 2014). Regarding the effects on dairy cattle, which experience heat stress when exposed to hot ambient conditions, the frequency of days leading to heat stress already rose during the past decades in several regions (Solymosi *et al.*, 2010). However, it must be kept in mind that many of the recently published studies do also show that the effects of climate change vary extremely concerning region, duration and distribution. In addition, the impact will be very different between livestock species, breeds and individuals. Therefore, key factors for every geographical area of interest, species (genotype) and intensity

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[†] E-mail: Matthias.Gauly@unibz.it

of the system must be identified. This review will focus on Europe and dairy cattle production systems.

The main effects of climate change, with significant effects on animal physiology, welfare, health and reproduction and therefore relevant for livestock production, are the increased frequency of hot days, heat waves, warm periods and other extreme weather conditions (e.g. floods and hail) (Zampieri *et al.*, 2016). It can be assumed that each part of the value chain in the dairy production will be influenced by climate change, particularly extreme conditions. For instance, literature shows that the milk yield as well as its composition is impaired by heat waves, which finally also affect various dairy products in terms of quality and quantity (Cowley *et al.*, 2015). Consequently, climate change comes along with significant economic impacts in the dairy sector. Thus, there is a necessity to develop mitigation strategies that contain management measures, nutritional adaptations, health maintaining factors as well as plant- and animal breeding programs that include heat tolerance to deal with these challenges. If such strategies are established, some authors estimated that climate change–associated economic impacts could be rather neutral than negative in Central Europe (e.g. Fitzgerald *et al.*, 2009).

How can climatic conditions and the effects on animals be quantified?

Potential influences arising through climatic conditions on cattle can be evaluated by using either (a) environmentally based parameter, (b) animal-related traits or (c) a combination of both. Regarding the environmental conditions, appropriate factors are air temperature, relative humidity, solar radiation, wind speed and precipitation. However, often indices combining some of these parameters are used to quantify the effects of heat load on animals and to estimate their thermal comfort zone. Limitations are the availability and validity of some parameters. Therefore, most studies have focused on the easiest available data, which are air temperature and relative humidity. Based on these, one of the most commonly used indices is the Temperature-Humidity-Index (**THI**), which combines air temperature and relative humidity differently weighted in a single value. A number of available THI formulas are developed in various climate regions with higher or lower prioritization of the ambient humidity in the formula. They also differ in the use of the parameter indicating the humidity (relative humidity, wet bulb temperature, dew point temperature) (Berman *et al.*, 2016). The use of different indices in different regions and parameters will therefore lead to different thresholds, which affects the transferability of THI thresholds. Most studies, carried out in moderate climate zones such as Central Europe, used the THI calculated by the National Research Council (1971), which combines air temperature (in °C) and relative humidity (in %). Other less common indices are the Back Globe Humidity Index (**BGHI**) (Buffington *et al.*, 1981), the Heat Load Index (**HLI**) (Gaughan *et al.*, 2009) or the Comprehensive-Climate-Index (**CCI**) (Van Laer *et al.*, 2015). The latter two include, besides air temperature and humidity, the ambient wind speed and solar radiation, which could be more reliable to assess climatic impacts on pasture compared to indoor conditions.

Although the assessment of thermal comfort or discomfort in dairy cattle based on the THI is widely investigated and commonly applied, there are some limitations concerning the utilization of this index in terms of validity, sensitivity and reliability. Besides regional and also farm-based variations in the evaluation of climatic conditions, it is widely known that individual traits of animals, for example, performance, pregnancy, breed, influence the vulnerability toward heat stress in dairy cattle (e.g. Renaudeau *et al.*, 2012). That confirms that measuring solely the THI to assess the occurrence of heat stress reliably seems to be not sufficient. Thus, when assessing heat stress in dairy cattle, animal-based observations must be taken into account additionally. Alterations in physiological parameters, for example, body temperature or respiration rate, give information about short-term responses to hot conditions, while effects on animal behavior and performance (mainly daily milk yield) are rather obvious after a longer heat period (e.g. Lambertz *et al.*, 2014). To represent body temperature, rectal temperature is the most commonly used parameter in cattle (Liang *et al.*, 2013), followed by vaginal and milk temperatures (Galán *et al.*, 2018). Other locations for measuring body temperature included the udder, rumen (Liang *et al.*, 2013), peritoneum or tympanum (Ammer *et al.*, 2016). The aim of monitoring the temperature for each of the several body locations is to represent the body core temperature in the best way possible based on a less-invasive method with high practicability. However, it must be kept in mind that any type of body temperature measurement is subjected to a number of external factors as season, time of day, climatic conditions as well as endogenous parameters like breed, milk yield, parity, water and feed intake and even the measuring method (Liang *et al.*, 2013; Ammer *et al.*, 2016). Other animal-based indicators are physiological indicators (e.g. respiration rate, heart rate, sweat rate, metabolic heat production), behavioral traits (e.g. feeding, resting, drinking, grazing) and biomarkers that aid the diagnosis of heat stress–induced metabolic disorders. These parameters may be useful to develop mitigation protocols that can be used before severe health or production problems appear (Galán *et al.*, 2018). In addition, the change of biochemical, cellular and metabolic parameters that occur during heat stress could also be helpful indicators in the future. As already mentioned earlier, effects of heat stress on animal performance and behavior traits also depend on the exposure time and duration of heat load. Thus, for example, the DM intake (**DMI**) is strongly influenced by the climate from the previous day than by the present conditions (de Andrade Ferrazza *et al.*, 2017). In moderate climate, even a period of 3 consecutive hot days is needed before heat stress affects milk yield significantly (Lambertz *et al.*, 2014).

Climate change, performance, product quality and reproduction

When climatic conditions, for example, the ambient temperature, exceed the upper limit of the individual thermoneutral zone, the heat dissipation of the organism must increase and further the body temperature increases. Both the organism itself and its performance are directly and indirectly affected by this heat load. However, the level of hyperthermia is significantly related to that of milk production. That is why a strict quantification of the lower and upper critical limits of the thermoneutral zone for dairy cattle in general is hardly feasible. However, the mentioned negative relation between ambient heat and feed intake becomes stronger with high milk yields. A reduction in feed intake results in a decrease in heat production of the organism itself, and this reduction is required for balancing the thermal load. Thus, it is obvious that high-producing dairy cattle are more vulnerable to heat stress (Zimbelman *et al.*, 2010).

Regarding milk yield, obvious climatic effects do not occur immediately, but rather they are delayed. West *et al.* (2003) estimated that a decrease in milk yield and DMI was caused by hot conditions of 2 days previously (THI between 72.1. and 83.6). According to Bouraoui *et al.* (2002), daily THI and milk yield as well as feed intake are correlated at −0.76 and −0.24, respectively. When THI exceeded 69, daily milk yield declined by 0.41 kg per rising index unit. In addition to milk yield, climatic impacts on the organic and inorganic milk ingredients were investigated with various results. Regarding milk lactose, one of the main ingredients following water, all studies have shown that there is no effect (Cowley *et al.*, 2015). Controversial results have been published for the effects of heat stress on milk fat content. Changes in triacylglycerol (**TAG**) profile and reduced phospholipid levels caused by heat stress were described by Liu *et al.* (2017), what might modify the characteristics of milk fat (e.g. fatty acid composition). However, Cowley *et al.* (2015) did not find any changes in the milk fat proportion under heat stress conditions, while heat stress tends to decrease both milk protein and casein content. This affects the milk coagulation properties and the efficiency of cheese manufacturing processes (Cowley *et al.*, 2015), especially when using raw milk. Concerning the mineral content of milk, Mariani *et al.* (1993) found significant seasonal variations, which are probably caused by different factors like feed.

Fertility impairments are probably the most important effects of heat stress for dairy farmers. The increase in internal body temperature related to short- and long-term heat stress is responsible for the impaired reproductive performance of dairy cattle. Heat stress impacts on fertility include an increase in the number of days open, reduced fertility due to anestrus and reduced conception rates (Kadokawa *et al.*, 2012). The effect of heat stress involves alterations in the follicle development (including the temperature of preovulatory follicles) and its enclosed oocyte (Campen *et al.*, 2018) and embryos. *In vivo* studies indicated a positive correlation between high temperatures at the day of insemination and conception rates (Nabenishi *et al.*, 2011). Sakatani *et al.* (2015) used an *in vitro* model to estimate the effect of heat stress on the fertilization of cow oocytes and concluded that arising oxidative stress leads to polyspermy, reducing the capacity of the zygote for a further development. Pregnant cows can be affected by heat stress through direct effects on the uterus, embryo and early fetus. On the other side, advanced-stage embryos (i.e. morula, blastocyst) have acquired a certain level of thermotolerance (Paes *et al.*, 2016). Various hormonal treatment strategies to minimize the mentioned effects on farm level were investigated. An improvement in the conception rate could be achieved through GnRH application in the artificial insemination (e.g. López-Gatius *et al.*, 2006). But the strategy is limited to cows that do show estrus. However, the effects of such hormone programs demonstrated under conditions of heat stress are controversial (e.g. Akbarabadi *et al.*, 2014). Besides the direct effects of heat stress on reproductive performance, reciprocal effects are of importance. Roth and Wolfenson (2016) summarize the effects of heat stress and intramammary infections on ovarian function in dairy cattle and how the two stressors are interacting. They postulated that both stressors, mastitis and heat stress, have an additive negative effect on fertility. In any case it is important to stress the fact that heat load may also have not only short-term but also long-term effects on the reproductive physiology of a cow (Safa *et al.*, 2019).

Furthermore, heat stress effects on the fertility of bulls were the objective of various studies. They reported adverse effects of testicular hyperthermia on sperm quality parameter and DNA integrity. Ejaculates of heat-stressed bulls showed decreased motility rates and increased proportions of morphologically abnormal sperms (Malama *et al.*, 2017). The retrospective study by Sabés-Alsina *et al.* (2019) on sperm-quality of frozen-thawed semen demonstrated that sperm quality parameters are more likely to be correlated with climatic factors 1 or 2 months before semen collection than in the month of semen collection. Because especially dairy bulls kept in commercial artificial insemination centers can be more easily protected by proper housing and management conditions, only little attention was given to this topic at this review.

Climate change, animal health, behavior and welfare

The effects of climatic changes on animal health, behavior and welfare will be either direct or induced indirectly due to consequences of other impairments. The impacts are modified by factors like animals' genetic material, the level of exposure and specific physical status (e.g. pregnancy). It is considered that as the production level increases, the sensitivity and vulnerability to stress (Sanker *et al.*, 2013) and therewith the impact on health, behavior and welfare increases. However, intensive production systems might be less affected compared to extensive systems, especially in least-developed countries, where no adaptation strategies are available (Rust, 2019).

Animal health can be directly affected by climatic conditions leading to temperature-related illness and death. These effects might be caused by changes in the immune and endocrine system (Das *et al.*, 2016). Seasonal influences on milk somatic cell count with increasing values during summer months are commonly reported (e.g. Testa *et al.*, 2017).

Indirect climatic effects on health as changes in feeding behavior (e.g. increase intake of concentrates, decrease in forage intake) of heat-stressed cattle can strengthen the development of acidosis, which might cause the occurrence of lameness in cattle. In addition, the reduction in feed intake in high-yielding dairy cattle increases the risk to experience subclinical or clinical ketosis during summer months (Lacetera *et al.*, 1996) as they have high energy requirements for maintenance and performance that must be subsequently mobilized.

Indirect effects of climatic changes on behavior and welfare of animals are more complex and thus less practicable in measurement and determination. They are linked to changes in availability of feed and water as well as their quality and the survival and distribution of pathogens and vectors. Polsky and von Keyserlingk (2017) concluded that more research is needed to better understand the pain, frustration, aggression and malaise associated with heat stress, especially increased hunger and thirst in the short term and foot lesions and lameness in the long term. However, it is known that only a short period of heat stress during the final phase of gestation can have intensive impacts on health, growth and performance of the calves associated with a long-term effect on these animals (Laporta *et al.*, 2017).

Potential changes induced by climate change include, for example, pathogens and vectors. The prevalence and distribution of pasture-borne parasitic helminth (nematodes and trematodes) infections are given as a prominent example. These infections show recent changes in epidemiology, seasonality and geographic distribution coming along with the effects of climate change (Morgan *et al.*, 2013). These complex changes in parasites and vectors epidemiology require innovative solutions. The studies and their outcomes depend very much on region and season. In order to develop a better regional adaptation strategy, a systematic monitoring ofclimate-driven changes across Europe was suggested (Charlier*et al.*, 2016). Such strategies must include certain management strategies like indoor or outdoor rearing of animals, the use of new diagnostic tools, innovative control approaches, the sustainable use of drugs and the rational integration of future control practices (Vercruysse *et al.*, 2018). Databases that include information on climate, the region and the distribution of pathogens could provide essential knowledge for effective control strategies. Climate change influences both the distribution and population dynamics of the vector and the virus. The Rift Valley fever virus is an insect-transmitted abortogenic virus whose distribution changes with the distribution of the insect vector related to climate change (Rolin *et al.*, 2013). In any case, optimal mitigation strategies to deal with pathogens and vectors will be highly system specific and also depend on respective management measures. With a stronger focus on mitigation and adaptation measures for livestock the impacts of climate change–associated diseases could be minimized (Bett *et al.*, 2017).

Heat stress is also detectable by behavioral alterations such as a reduction and/or changes in activity (Cook *et al.*, 2007), increased water intake, reduced feed intake (Ammer *et al.*, 2017) or a shift in feed intake to colder times of the day. Allen *et al.* (2015) described changes in standing and lying behavior of heat-stressed dairy cattle what might further decrease obvious estrus signals such as mounting. According to Heinicke *et al.* (2019), heat stress led to a reduction in the activity of dairy cattle, while animals in the early lactation were less sensitive compared to later-lactating cows. Besides they proved individual cow-related factors. Allen *et al.* (2015) speculated that standing may help to cool cows and is therefore increasing in time under heat stress, what might additionally affect the milk production for what longer lying periods are required.

Climate change, feed and dairy cow nutrition

Feed production will be influenced by an increase in atmospheric CO_2 levels, temperature (Chapman *et al.*, 2012) and decreased water availability and distribution. Several models have been published to estimate the productivity of grassland and the nutritional value under the scenario of climate change (e.g. Ma *et al.*, 2015). Phelan *et al.* (2016) showed a positive relation between the duration of the grazing season and the climate change in Europe. The authors predicted that most European countries will have a net increase of grazing season by up to 2.5 months.

On one hand, it is assumed that forage yield will increase due to climate change (especially in the north); however, on the other hand the quality of feed that mainly depends on water availability will be negatively affected. Craine *et al.* (2010) analyzed more than 21 000 cattle fecal samples to estimate the effects of climatic conditions on protein and energy availability in forage. They found reduced CP and digestible organic matter in the diet with higher temperatures and less precipitation in continental climate regions. Therefore, besides direct heat stress effects cows will experience additional burden due to future nutritional changes, particularly with increasing milk yields. However, it demonstrates once again that arising effects on feed amount and quality might differ between regions, systems and animals. The plant composition grassland systems need adaptations to species that are resilient to changing conditions (Gauly *et al.*, 2013). For instance, deeper rooting legumes could be able to use water that is not available for other species; thus, cultivating species in diverse swards might advance the water utilization of grassland (Chen *et al.*, 2007), and additionally improve the dietary digestibility for ruminants (Perring *et al.*, 2010). Besides cultivation strategies, managing the grassland (e.g. time of cutting, fertilizer type, grazing length) might provide essential options to handle climatic effects on feed production (e.g. Holden *et al.*, 2008). Irrigating the land would also increase yields, but through restrictions in water availability this option is limited to certain regions.

The effects of several feeding strategies aiming to reduce negative impacts of heat periods on the dietary supply of dairy cattle and their performance (e.g. yield, fertility) have been studied in the past decade (e.g. Kaufman *et al.*, 2017). Results have been more or less promising. It is known that dairy cattle under heat stress prefer the consumption of concentrates compared to roughage, as the fermentation processes of roughage come along with metabolic heat load. However, increasing the concentrate amounts in the diet limits a ruminant-adapted nutrition.

Feed additives (e.g. vitamins) were investigated for their effects to improve the animals' ability coping with heat stress. The vitamin niacin was tested for its effects on blood vessels (vasodilatation) and lipid metabolism. Zimbelman *et al.* (2010) showed that cows fed rumen-protected niacin had lower rectal and vaginal temperatures under moderate heat load. Among feed additives, controversial results were found for the effects of increasing the energy density in the ration of high-yielding cows under hot and humid climates and the effects of functional oils (oils that have functions beyond their energy value like castor oil, which comes from *Ricinus communis*) (Ghizzi *et al.*, 2018) and/or fat (Moallem *et al.*, 2010). Wang *et al.* (2010) showed that feeding supplemental saturated fatty acids (**SFA**) during heat stress decreased the body temperature during the hottest time of the day and increased milk yield. The authors believe that this was caused by reducing the development of metabolic heat by the replacement of fermentable carbohydrates with supplemental SFA.

Climate change and dairy husbandry

Managing a dairy herd around frequent and intensive heat periods, particularly high-performing animals, is highly demanding for farmers and accompanied with growing challenges. Several options are available on the level of the husbandry and management system, including structural alterations/adaptations like cooling techniques; provision of adequate shade (Kendall *et al.*, 2007); management of feeding times, for example, shifting to cooler periods in the evening, night and early morning (Legrand *et al.*, 2009), to minimize heat stress in dairy cattle. Alteration in feeding times to the evening or early morning might reduce the heat load simultaneously to daytimes with high ambient temperatures (Nikkhah *et al.*, 2011). However, according to Ominski *et al.* (2002) this does not influence vaginal temperature, feed intake and performance of heat-stressed dairy cattle.

Available cooling systems are fans, misters, sprinklers and cooled waterbeds. Possible modifications are including new technologies like tunnel ventilation (Calegari *et al.*, 2012). Efficient cooling systems are meanwhile obligatory in order to reduce heat stress in dairy cattle. One option is a short-term spraying of water which is further evaporated supported by fans in the barn. Similar systems are commonly used worldwide so far, particularly in hot regions. Kendall *et al.* (2007) compared the efficiency of three different cooling systems: shade, sprinklers and combination of shade and sprinklers. They demonstrated clearly that the combined approach of shade and sprinklers (67% reduction in respiration rate) and only sprinklers (60%) were more effective than solely providing shade (30%). Avendaño-Reyes *et al.* (2010) compared three cooling management systems by changing time and duration of cooling through vents to alleviate heat stress during hot conditions. The authors assumed that the cooling period must be extended for improved effects. In addition, a higher frequency of cooling periods per day in which sprinkling and ventilation are combined leads to increasing cooling results. Several studies described the effects of cooling on the reproductive performance. Honig *et al.* (2016), for example, found positive effects of cooling management on ovary functions, estrus cycle length and overall fertility of dairy cattle under heat stress. The sole provision of shade is less efficient compared to the use of sprinkler concerning the cooling capacity after cows were exposed to heat load on pasture in summer. However, when taking the cows' preference into account more cows (65%) have chosen shade instead of sprinklers (Schütz *et al.*, 2011). Besides the effect of a reduced temperature due to shade, the greater effect on the heat load is represented by a lower solar radiation within the shade. Positive effects of shade on animal performance were reported, for instance, by Van Laer *et al.* (2015).

Climate change and genetics

Many adaptation strategies to climatic changes consider short-term effects on animals during an intensive heat period. However, they do not lead to a long-term solution of the problem. A genetic adaptation of the animals, which means involving resilience to thermal load as a functional trait in breeding programs, could be a long-term strategy in dairy cattle (Al-Kanaan *et al.*, 2015). Therefore, heat stress–correlated traits like the cows' ability to obtain a stable rectal temperature could be implemented into selection indices. Other potential breeding traits could be, for example, hair coat color. Anzures-Olvera *et al.* (2019) concluded that Holstein cows with dominant black hair kept in a hot environment moderately reduced milk yield without effects on its composition, body temperature and reproduction. Heat-tolerant animals have a greater ability to maintain their core body temperature under changing climatic conditions. It varies between breeds and individuals that might also reflect milk yield differences (Dikmen and Hansen, 2009). When investigating heat tolerance traits of cows (e.g. variation in body temperature, respiration rate, heart rate under hot conditions) they should be measured most effectively under heat stress (Ravagnolo *et al.*, 2000). A limitation of this approach might be the availability of valid measures for heat tolerance from already-existing data that were recorded with different objectives. Meanwhile statistical models to estimate heat tolerance and breeding values for heat tolerance have been developed and implemented in some breeds and parts of the world (Nguyen *et al.*, 2017). Selection for heat stress, in combination with other traits that contribute to profitability, is timely to prevent further deterioration in tolerance of heat stress. Ravagnolo *et al.* (2000) estimated a heritability for milk yield of 0.17 when THI values were below 72, and an additive variance of heat tolerance not significantly different from 0.0. The genetic correlation was −0.36. The values for fat and protein were similar. If heat stress persists, the expression of involved genes changes, leading to alteration in the physiological state, what leads an adaptation (Collier *et al.*, 2008). Nguyen *et al.* (2017) developed genomic estimated breeding values for heat tolerance in Australian dairy cattle. Correlations with other breeding values suggested that heat tolerance had a favorable genetic correlation with fertility but unfavorable correlations for some production traits. Aguilar *et al.* (2009) estimated genetic components of heat stress in Holstein cows. The estimated genetic variance increased with proceeding parities. Genetic correlations were between 0.84 and 0.98 for general additive effects, while the correlation for milk yield was approximately −0.45 and differed between parities and stage of lactation. Even though Bohmanova *et al.* (2008) found similar estimated breeding values for heat tolerance, potential genotype to environment interactions must be considered. However, Bernabucci *et al.* (2014) summarize for their studies that the genetic component of heat tolerance is essential and should be part of the selection objectives.

It is well known that breeding for high yields came along with higher vulnerability to climate extremes. Such negative relations like those between reproductive efficiency and milk yield, although relatively low, also appear in breeds that are more heat-tolerant like Zebu cattle (Berman, 2011). Differences in heat tolerance are very well described for breeds (e.g. Souza-Cácares *et al.*, 2019). These breeds are especially warm climate breeds (Zebu and Sanga cattle) that adapt to the climate conditions in which they are developed (Berman, 2011). Genetic differences may be caused by various differences in characteristics like number of sweat glands, their morphology and water transfer capacity (Pereira *et al.*, 2014). However, it is not self-evident that such morphological differences also lead to functional differences (Berman, 2011). Some breeds are able to produce higher amounts of certain heat shock proteins (**HSP**) which could be involved in the mechanisms of adaptation to heat conditions (Souza-Cácares *et al.*, 2019).

Conclusions

Climate change already has and will further come along with significant impacts on the dairy sector. The effects will be both direct and indirect. The impacts on dairy production systems can be categorized as (1) the availability and quality of feed and water, (2) the effects on health and performance and (3) the effects on disease and the spread of vectors. This will lead on the production level to higher mortality rates, impaired immune functions and greater distribution of infectious diseases, reproductive impairments, alterations in feed intake and growth and reduced milk yields, particularly in high-producing dairy cattle, altogether leading to economical disadvantages. Therefore, there is an essential requirement to develop effective mitigation and adaptation strategies involving husbandry systems, management, nutrition, health as well as plant and animal breeding (e.g. breeding for heat tolerance) for long-term solutions.

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M. Gauly 0000-0003-4212-5437

Declaration of interest

The authors declare that they have no conflict of interests.

Ethics statement

None.

Software and data repository resources

None.

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