Impacts of heat stress on global cattle production during the 21st century: a modelling study

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Summary

Background Heat stress in animals is one of the major climate change impacts on domesticated livestock raised in both intensive and extensive production systems. At temperatures higher than an animal's thermoneutral zone, heat stress can affect liveweight gain, milk yield, and fertility. Animal welfare may also be negatively affected by heat stress even in the absence of effects on productivity, at least in the short term.

Methods We estimated the comparative statics change in the value of cattle milk and meat production from heat stress-induced losses at the global level, using climate scenario outputs for the middle (2045) and end of the century (2085). The loss estimates are based on bioenergetic equations that relate changes in dry matter intake (DMI) to both cold and hot, humid weather. DMI changes were estimated using CMIP6 climate data and linked to a global dataset containing information on livestock production systems, animal numbers, and region-specific and system-specific animal diets. Changes in DMI were converted to changes in milk and meat production and valued using early 20th century world prices (ie, constant 2005 US dollars).

Findings For a high greenhouse-gas emission scenario (SSP5-8.5), production losses from heat stress were estimated to amount to \$39·94 billion (95% CI 34·39–45·49 billion) per year by the end of the century, or 9·8% of the value of production of meat and milk from cattle in 2005. For a low emission scenario (SSP1-2.6), the value of production losses was \$14·89 billion (12·62–16·95 billion) per year, or 3·7% of 2005 value. In both scenarios, losses in most tropical regions were projected to be far greater than they were in temperate regions.

Interpretation Our results highlight the potential magnitude and extent of the adaptation efforts that will be necessary to combat the effects of increasing heat stress on cattle production during this century if food security challenges are to be minimised. Adaptations include switching to more heat-tolerant breeds and provision of shade, ventilation, and cooling systems.

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Introduction

Heat stress results from a combination of several weather variables including high ambient temperature, humidity, solar radiation, and wind speed, with negative impacts on both animal welfare and productivity. Depending on species and breed, cattle can experience thermal stress at temperatures higher than 20°C.[1] At higher temperatures, animals reduce their feed intake by 3–5% per additional degree of temperature, reducing productivity.[2,3] Heat stress increases respiration and mortality, reduces fertility, modifies animal behaviour, and suppresses the immune and endocrine system, thereby increasing animal susceptibility to some diseases.[4–7] These changes can affect the economic performance of dairy and beef production systems.

The escalating demand for livestock products in low-income and middle-income countries coupled with steadily increasing temperatures is an uncomfortable mix, with costly infrastructural investments possibly required if domestic livestock are to adapt to new thermal environments and increase their productivity simultaneously.[2] Previous studies estimated annual losses due to heat stress of US\$1·26 billion for dairy and beef cattle herds in the USA in the early 2000s, and income losses of £40 million in the UK dairy herd in some years by 2080 in the absence of mitigation measures.[5,8]

We aimed to produce new data for the potential global impacts of climate-change-related heat stress on dairy and beef cattle in terms of the potential value of losses in meat and milk production.

Methods

Study overview

We based our loss estimates on bioenergetic equations that relate changes in dry matter intake (DMI) in cattle to both cold and hot, humid weather. DMI changes were linked to an existing, peer-reviewed global dataset containing information on cattle production systems, animal numbers for the year 2005, and region-specific and system-specific animal diets.[9] We then estimated milk and meat production and the differences in production in

Research in context

Evidence before this study

Considerably fewer studies have focused on the varied impacts of climate change on livestock production than on crop production. Nevertheless, a substantial literature exists on the effects of heat stress on cattle physiology and resulting impacts on the production of meat and milk. Much of this work has been undertaken for more intensive dairy and beef production systems in the temperate regions. We searched Web of Science and Scopus databases for regional and global reviews of the potential effects of increased heat stress due to anthropogenic warming during the present century. We found some studies at national and regional scales that compared heat tolerance in different meat and milk cattle breeds, and some that estimated impacts of heat stress at these scales on cattle production using CMIP5 climate data and that were used in Intergovernmental Panel on Climate Change (IPCC) special reports. A consistent analysis of the extent and severity of heat stress on cattle production systems at the global level was lacking, as were studies that made use of the latest CMIP6 climate data prepared for the three Working Groups of the IPCC's Sixth Assessment Report being published in stages in 2021 and 2022.

Added value of this study

We combined a detailed global database on cattle production systems, representative diets, and harmonised dairy and beef cattle numbers with CMIP6 climate data and bioenergetic equations to estimate the impacts of global warming from early century through to end century on heat stress in cattle, its effect on dry matter intake, and the resulting impacts on meat and milk production. We used a comparative statics approach to develop the first global estimates of projected changes in the value of production of cattle meat and milk, by production system at national level, as a result of increasing heat stress effects, in the absence of adaptation. This is one step in understanding the approximate magnitude and extent of the heat stress problem that will face livestock producers in different countries and in different production systems. This analysis can form the basis for more detailed studies of impacts to inform context-specific adaptation options in the future.

Implications of all the available evidence

Heat stress will become an increasingly serious challenge in cattle production systems as the current century progresses. In the lower latitudes, large parts of tropical central and South America, southeast Asia, and west and east Africa—with the exception of the highlands of central Ethiopia and south-western Kenya—will be affected. Significant but lower impacts are projected in parts of the higher latitudes. Production costs, such as increased cooling and building costs, are likely to increase in all cattle systems in the future as a result of the adaptation required. More nuanced analyses that include additional factors such as the impacts of extended periods of heat stress on different breeds of cattle and their welfare are needed to prioritise context-specific adaptation interventions and to identify the limits to adaptation using current technology, beyond which outdoor livestock production might not be possible.

early-century (2005), mid-century (2045), and end-century (2085) climates under a low and high emissions scenario. Taking a comparative statics approach, we used 2005 prices to value the potential changes in meat and milk production due to increasing heat stress scenarios throughout this century.

See Online for appendix

To estimate heat stress effects on animal DMI, we calculated dry matter adjustment factors based on the Current Effective Temperature Index (CETI):[10]

$$\begin{aligned}\mathrm{CETI}=&27\cdot88-(0\cdot456\times\mathrm{Tav})+(0\cdot010754\times\mathrm{Tav}^2)\\&-(0\cdot4905\times\mathrm{RH})+(0\cdot00088\times\mathrm{RH}^2)\\&+(1\cdot1507\times\mathrm{Wsp})-(0\cdot126447\times\mathrm{Wsp}^2)\\&+(0\cdot019876\times\mathrm{Tav}\times\mathrm{RH})-(0\cdot046313\times\mathrm{Tav}\times\mathrm{Wsp})\\&+(0\cdot4167\times\mathrm{Hrs})\end{aligned}$$

where Tav is the average daily temperature (°C), RH is the average daily relative humidity (%), Wsp is average daily windspeed (km per h), and Hrs is the hours of direct sunlight per day to which the animal is exposed.

The DMI adjustment factor ($\mathrm{DMI_f}$) to account for heat or cold was estimated as follows:[3]

$$\begin{aligned}\mathrm{DMI_f}=&a+b\times(2\cdot0\times e\times(\mathrm{Ln}(\mathrm{Exp}((\mathrm{CETI}+d/2)/e)\\&+\mathrm{Exp}(c/e))-\mathrm{Ln}(\mathrm{Exp}((c+d/2)/e)+\mathrm{Exp}(\mathrm{CETI}/e))\\&+d)/(2\times d)\end{aligned}$$

where CETI is as defined previously and a, b, c, d, and e are coefficients (appendix p 3).

These equations form part of the widely used Cornell Net Carbohydrate and Protein System (CNCPS) model[11] and the impacts of ambient temperature on DMI have been validated by Tedeschi and Fox[3] using these equations against a wide range of data. As these equations are not specific to any region, production system, or breed, they provide the basis for a consistent, global analysis. Here we captured regional variations through the use of the Herrero and colleagues dataset,[9] which assigns different diets to cattle in different production systems (eg, livestock grazing, mixed [with both crops and livestock on the same farm], and other systems, located in humid–subhumid, arid–semiarid, temperate, or tropical highland climates), based on available resources and level of livestock production. For each of seven production systems and each of nine regions (appendix p 3), Herrero and colleagues formulated typical diets for beef and dairy cattle using four types of feed: grazed grass, crop residues (stover and straw), grains (grain-based supplements), and other feeds (including cut-and-carry fodders, legumes, and other planted forage). The percentage of each feed type in the diet was obtained from extensive literature reviews. The make-up of the system-by-regions and nutritional quality data are presented in supplementary table 10 in Herrero and colleagues.[9] Cattle diets, meat and milk production, and cattle numbers were harmonised on the basis of tropical livestock units (TLU), one TLU being equivalent to an adult animal weighing 250 kg.

To implement the calculations of the DMI adjustment factor from the climate data available, we used average daily minimum temperature as a proxy for lowest night temperature and set the hours of direct exposure to sunlight to zero, given that cattle actively seek shade to minimise direct exposure to the sun in hot weather.[12] For each grid cell in the analysis, the monthly average CETI was calculated using average daily temperature, average daily relative humidity, and wind speed. The DMI adjustment factor was then calculated for the baseline year and for the future time slices and scenarios by summing DMI across all relevant feed components and calculating the reduction in energy of the diet.

Climate data

We used climate data for two future scenarios, a shared socioeconomic pathway (SSP) 1 coupled with a low greenhouse gas (GHG) emission future, representative concentration pathway (RCP) 2.6, and SSP 5 coupled with RCP 8.5, a very high GHG-emission future. These two SSP-RCP combinations were chosen as they cover the full range of scenarios to the end of the century as envisaged by the Intergovernmental Panel on Climate Change (IPCC).[13]

We used bias-adjusted, statistically downscaled outputs from five CMIP6 global climate models (MRI-ESM2-0, IPSL-CM6A-LR, MPI-ESM1-2-HR, UKESM1-0-LL, and GFDL-ESM4) using the ISIMIP3b simulation round, for current and future time slices as projected in response to SSP1-2.6 and SSP5-8.5.[14,15] We calculated ensemble 20-year climatologies for early-century (1996–2015), mid-century (2036–55), and end-century (2076–95) from the following variables: average monthly mean daily temperature, average monthly minimum daily temperature, average monthly maximum daily temperature, and average monthly daily wind speed.

We estimated the monthly average maximum and minimum daily relative humidity (RH_{max}, RH_{min}) from the dew point temperature (Td), itself estimated from the mean daily temperature and the diurnal temperature range.[16] Values for RH_{max} and RH_{min} were calculated from Td and the vapour pressure.[17] The average daily RH value was calculated as the mean of RH_{min} and RH_{max}.

Production and economic impacts at scale

Following Herrero and colleagues,[9] our analysis was based on the livestock system classification in Robinson and colleagues.[18] This classification distinguishes between grazing systems, mixed-crop livestock systems, and landless livestock systems. The land-based systems are further broken down based on agroclimatic conditions (arid–semiarid, humid–subhumid, and temperate or tropical highland areas). The numbers of animals in each system and region were from Wint and Robinson.[19] for the year 2000, harmonised with national totals for 2005.[9] Herrero and colleagues[9] derived separate herds for the production of milk and of beef using herd dynamics models parameterised for each region and production system using reproduction and mortality rates from the literature. Each herd contains disaggregated numbers in TLU of dairy adults and replacement animals by country and by system.

In Herrero and colleagues,[9] data for the quantity and quality of the different feeds was used to parameterise an IPCC tier 3 digestion and metabolism model, which estimates production of milk and meat, manure production, nitrogen excretion, and methane emissions using stoichiometric calculations. It is a non-linear mechanistic model of ruminant digestion that represents the basic biology of feed intake, production, and emission, based on widely accepted principles.[20,21]

For animal numbers, all bovine milk and meat production was harmonised with country-level data for the baseline year, 2005.[9] That study[9] (and this one) used global average commodity prices for meat and milk for 2005[22] to estimate the value of the losses of animals and animal products (milk and meat). We carried out an uncertainty analysis by calculating the annual price variability for the years 2001–10[22] and derived 95% CIs for the global value of the production losses in meat and milk.

Estimations of milk and meat loss

To estimate milk production losses in the dairy herd, the system-by-country reduction in energy intake was converted into kg of milk production lost on the basis that production of 1 kg of milk requires approximately 5 MJ of metabolisable energy.[20,23] Production losses by country by system were then estimated by multiplying the number of adult animals in the country-by-system herd in TLU by the amount of lost production per TLU.

For more on **ISIMIP3b** see https://www.isimip.org

To estimate the effects of DMI reduction on liveweight gain of the dairy herd (mature animals and replacements) and the beef herd (mature animals and replacements), a similar procedure was followed. One kg of liveweight gain per TLU requires approximately 33 MJ metabolisable energy,[20,23] equivalent to a loss of 0·55 kg of meat.[24] The total reduction in meat production due to reduced DMI was then calculated. In some situations, we found that the reduction in dietary MJ metabolisable energy per TLU exceeded the energy content of the baseline meat production per TLU in that system in that country. In these cases, the additional energy loss was allocated to animal deaths, on the basis that maintenance energy requirements would not be able to be supplied to those animals. Mortality in the adult dairy herd was treated in the same way, and adult animal losses from the dairy herd added to animal losses from the beef herd. The energy requirement for maintenance of one TLU is approximately 40 MJ metabolisable energy per day or 14 600 MJ metabolisable

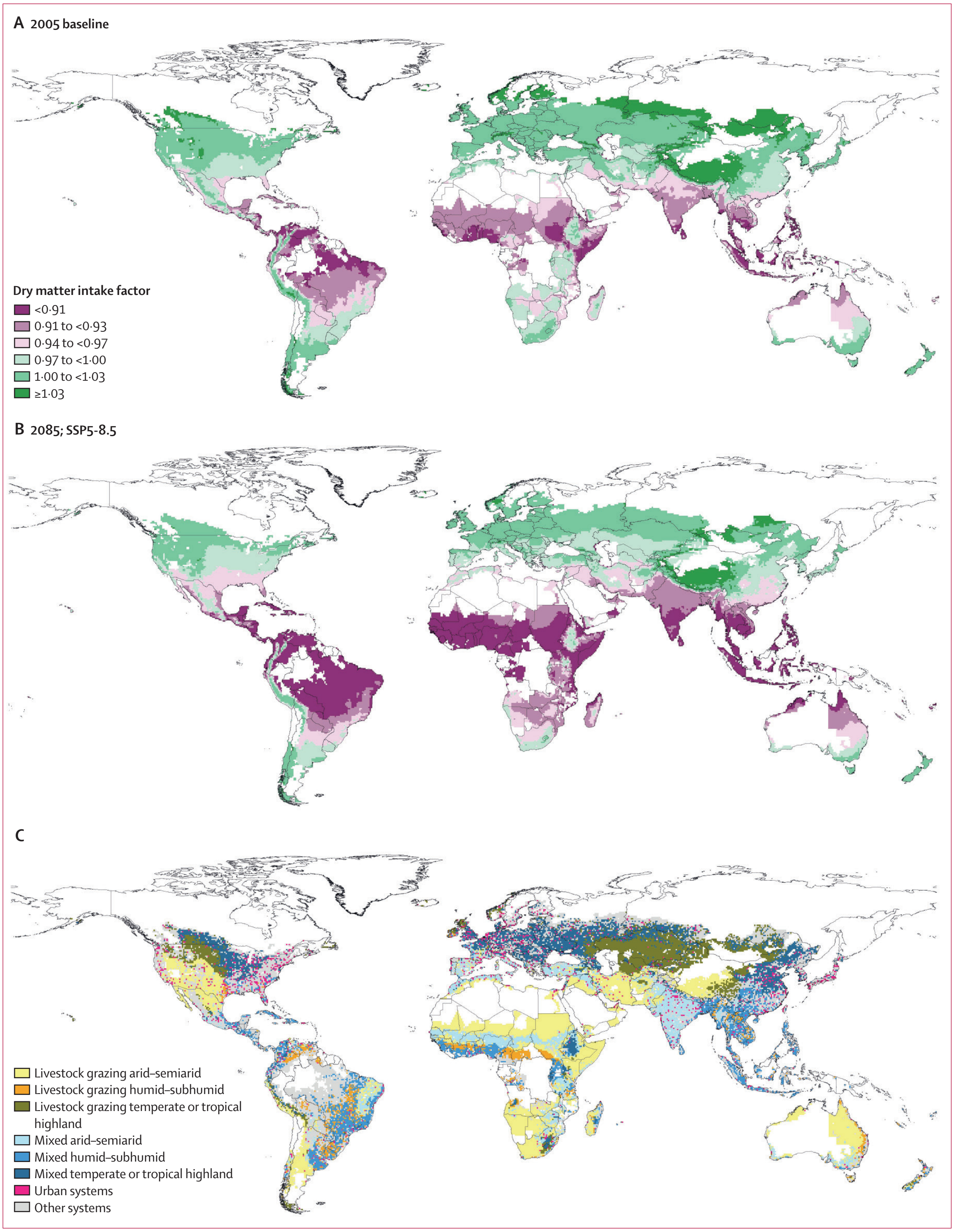

Figure 1: **Mean annual dry matter intake adjustment factor for cattle due to temperature stress**
(A) 2005 baseline, ISIMIP CMIP6 GCM ensemble. (B) End century assuming SSP5-8.5 impacts, ISIMIP CMIP6 GCM ensemble. (C) Underlying livestock production systems.[18]

energy per year, including allowances for walking.[20,23] In the absence of global distribution maps of cattle of different breeds or types, we applied this average value to both the beef and dairy herds. The number of TLU lost was calculated as the remaining unallocated MJ metabolisable energy remaining divided by 14600.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Annual averages of monthly DMI adjustment factors for early century and end century under SSP5-8.5, and livestock productions systems are shown in figure 1 and tabulated in appendix pp 5–24 by production system type and country for all scenario-year combinations. In colder climates, the adjustment factors are greater than 1 (ie, DMI is greater to compensate for the animal's higher energy maintenance requirement). In warmer, more humid places, the DMI adjustment factor is less than 1, reflecting reduced feed intake because of heat stress. For 2005 (early century), DMI was already constrained by heat stress to some extent in some regions (eg, humid–subhumid parts of west Africa, the east African coastal zone, and parts of northern South America and southeast Asia). Annual DMI factors increase as climate cools, and at the northern boundaries of cattle systems and on the Mongolian plateau, for example, DMI is higher to compensate for higher maintenance loads. Under SSP5-8.5, by end century the area of the tropics with DMI adjustment

	Livestock grazing			Mixed			Urban	Other	Weighted total
	Arid–semiarid	Humid–subhumid	Temperate or tropical highland	Arid–semiarid	Humid–subhumid	Temperate or tropical highland			
India									
Reduction, %	24·6%	9·9%	1·8%	5·0%	4·8%	2·8%	5·3%	6·7%	5·2%
Baseline, kg/day	1·1	7·2	10·9	7·7	10·1	17·1	6·1	6·1	7·7
USA									
Reduction, %	··	··	··	3·1%	2·6%	2·7%	2·6%	2·3%	2·7%
Baseline, kg/day	··	··	··	20·2	24·8	29·9	22·8	22·9	25·0
China									
Reduction, %	10·3%	8·4%	3·1%	18·6%	11·9%	4·2%	6·4%	6·8%	5·4%
Baseline, kg/day	1·1	5·4	9·8	1·9	3·4	13·1	7·2	7·4	9·1
Germany									
Reduction, %	··	··	··	1·1%	··	0·9%	1·4%	1·5%	1·1%
Baseline, kg/day	··	··	··	17·6	··	26·6	13·2	13·2	21·2
France									
Reduction, %	··	··	··	1·5%	1·1%	1·1%	1·9%	1·8%	1·2%
Baseline, kg/day	··	··	··	17·6	22·1	26·6	13·2	13·2	20·7
Brazil									
Reduction, %	7·0%	17·8%	9·6%	57·7%	11·3%	6·8%	24·2%	14·3%	13·1%
Baseline, kg/day	0·7	3·6	9·9	0·9	6·3	16·3	3·0	3·0	4·9
Russia									
Reduction, %	4·3%	··	4·7%	2·6%	··	3·6%	4·6%	2·9%	3·5%
Baseline, kg/day	3·7	··	8·8	11·2	··	14·0	9·0	9·0	11·2
Pakistan									
Reduction, %	28·7%	··	··	4·3%	3·8%	2·3%	5·6%	5·5%	4·8%
Baseline, kg/day	1·0	··	··	7·4	9·7	16·4	5·8	5·8	6·6
New Zealand									
Reduction, %	1·5%	1·1%	0·8%	1·3%	1·1%	0·7%	3·1%	1·5%	1·8%
Baseline, kg/day	8·6	17·7	23·6	9·1	17·9	22·0	10·2	12·4	14·0
Ukraine									
Reduction, %	··	··	7·0%	··	··	3·8%	5·4%	3·8%	3·9%
Baseline, kg/day	··	··	8·8	··	··	14·0	9·0	9·0	13·0

Data are projected percentage reduction from the 2005 milk yield and baseline milk production (kg per TLU per day) in 2005. Milk producers are shown in descending order of tonnes of milk produced in 2005.[22] One TLU is equivalent to an adult animal weighing 250 kg. TLU=tropical livestock unit. ··=no cattle in that production system.

Table 1: **Impacts of heat stress on milk production per TLU for the top ten milk producers by end century under SSP5-8.5**

factors less than 0·91 (ie, <91% of what the animal's DMI would be compared with an unstressed level of intake) increases substantially, to cover large parts of tropical central and South America, west Africa and east Africa (notable exceptions being the highlands of central Ethiopia and south-western Kenya), and large parts of southeast Asia (figure 1).

Impacts of end-century climate change scenarios on changes in DMI on milk production by system are shown in table 1 for the top ten milk-producing countries in 2005. Milk production values per TLU per day in 2005 are also shown, highlighting existing variation between production systems due to nutrition and local climate. For example, in India (the top global milk producer in 2005) milk production per TLU in the grassland-based, arid–semiarid system was projected to be reduced by nearly 25% in end century compared with 2005, even though the baseline milk production was very low in that system. Conversely, in the Indian mixed crop-livestock, temperate or tropical highland system, the milk yield reduction was only 2·8%; this system is a far more intensive production method, with cooler temperatures and lower levels of heat stress, and a much better quality and quantity of diet for adult milking animals and average milk yields in 2005 of 17·1 kg per TLU per day. The number-weighted percentage reductions in average milk yields per country across all systems (table 1) are modest, particularly for the higher-latitude countries. Brazil is an exception, with an estimated loss of milk production of 13·1% by end century under a high-emissions scenario.

Table 2 shows the end-century impacts on a per TLU basis for the top ten beef-producing countries in 2005.[22]

	Livestock grazing			Mixed			Urban	Other	Weighted total
	Arid–semiarid	Humid–subhumid	Temperate or tropical highland	Arid–semiarid	Humid–subhumid	Temperate or tropical highland			
USA									
Reduction, %	11·8%	9·8%	10·3%	5·5%	5·5%	5·4%	9·9%	9·3%	6·8%
Baseline, kg/year	49·9	59·8	54·8	185·8	201·6	267·7	76·4	76·4	63·7
Brazil									
Reduction, %	29·5%	20·5%	23·7%	45·3%	22·2%	13·4%	15·3%	42·6%	23·0%
Baseline, kg/year	37·9	77·1	77·1	40·8	79·3	168·4	16·1	126·0	32·7
China									
Reduction, %	42·9%	17·6%	5·8%	110·5%	46·2%	12·0%	13·2%	13·6%	14·9%
Baseline, kg/year	1·3	53·6	114·0	7·2	24·4	114·0	78·2	78·2	40·3
Australia									
Reduction, %	11·5%	11·2%	3·2%	8·3%	4·5%	4·0%	11·7%	10·6%	9·9%
Baseline, kg/year	106·8	91·6	152·3	119·2	102·5	174·0	79·4	79·4	106·8
Argentina									
Reduction, %	17·9%	11·9%	7·1%	20·0%	11·0%	0·3%	8·1%	13·7%	12·8%
Baseline, kg/year	28·1	69·9	57·3	24·8	63·0	190·8	61·8	96·0	28·1
Mexico									
Reduction, %	22·9%	13·1%	11·8%	27·8%	9·2%	5·7%	12·4%	12·6%	12·8%
Baseline, kg/year	35·3	71·9	71·7	31·2	133·7	252·0	79·4	79·4	35·3
France									
Reduction, %	6·6%	7·3%	5·8%	3·4%	2·4%	2·5%	5·6%	5·2%	3·3%
Baseline, kg/year	48·5	54·5	54·5	189·0	168·3	195·9	74·4	74·4	56·1
Russia									
Reduction, %	6·4%	··	6·4%	4·9%	··	5·7%	13·9%	8·8%	6·4%
Baseline, kg/year	90·3	··	172·6	210·2	··	371·0	90·0	90·0	98·4
Canada									
Reduction, %	1·6%	··	11·2%	··	··	3·1%	5·8%	4·5%	3·9%
Baseline, kg/year	57·7	··	26·5	··	··	150·7	88·5	88·5	52·6
India									
Reduction, %	42·2%	94·6%	5·6%	59·9%	36·2%	31·7%	24·2%	31·0%	45·1%
Baseline, kg/year	1·0	1·0	58·7	4·8	29·5	29·5	22·3	22·3	5·1

Data are projected percentage reduction from the 2005 beef yield and baseline beef production (kg per TLU per year) in 2005. Beef producers are shown in descending order of tonnes of beef produced in 2005.[22] One TLU is equivalent to an adult animal weighing 250 kg. TLU=tropical livestock unit. ··=no cattle in that production system.

Table 2: **Impacts of heat stress on beef production per TLU for the top ten beef producers by end century under SSP5-8.5**

The picture here is somewhat different from that of milk. Land-based beef production systems are generally relatively low-input, and diets are often of relatively low quality. The effects of DMI reductions are thus more pronounced than is the case with higher-input dairy systems. Production in the USA (the top beef producer in 2005) was projected to decline by 6·8% under SSP5-8.5 with end-century impacts. The countries in lower latitudes all see a greater production loss than the USA, while losses in higher latitude countries such as Canada, France, and Russia are lower. India is projected to lose 45·1% of its beef production due to increases in heat stress under SSP5-8.5 with end-century impacts. The reason is because Indian production of meat per TLU is extremely low, only 5·1 kg per TLU per year in 2005, so the great majority of dietary energy is used for maintenance of the animal rather than production. Despite low production levels per TLU in India, total production is large because of the number of animals: more than 200 million TLU in 2005.

We estimated the change in GHG emissions intensity arising from DMI reductions due to heat stress (ie, the enteric fermentation component of emissions). Overall, methane emissions from enteric fermentation were projected to decline by up to 2·0% for all scenario-year combinations compared with the baseline year, due to reductions in production and animal numbers as a result of increased heat stress (table 3). GHG emission intensities per kg milk and meat production for the top ten producers are shown on appendix p 121. These emissions increase from early-century to end-century, because as DMI decreases, less energy becomes available for production. The main consequence is that the maintenance requirement of the animal is a relatively larger fraction of the total requirement. As intake declines, emissions per animal are projected to decline but emissions per kg of meat or milk then increase.[25,26]

Global economic losses in milk and meat production are shown in table 4, ranging from $14·65 billion (95% CI 12·61–15·69 billion) annually for SSP1-2.6 for mid-century impacts up to $39·94 billion (34·39–45·49 billion) for SSP5-8.5 with end-century climate impacts. The results for SSP1-2.6 with end-century climate impacts are similar to those for mid-century, a consequence of global CO_2 emissions declining after peaking mid-century, eventually becoming negative in this scenario. Under SSP5-8.5, annual losses by end century are projected to be nearly double those in mid-century. For this scenario, 23% of the economic losses are from milk production lost, amounting to 4·7% of the global milk value of production in 2005, and 77% are from meat production lost, amounting to more than 14% of the global value of early century beef production. Appendix p 122 shows these economic losses disaggregated to system type, in terms of absolute losses and as a percentage of early-century production.

We found large regional variations in potential economic losses (figure 2, appendix pp 25–120, 123, 124). The region consistently hit the hardest, in terms of the percentage of meat and milk production potentially lost to both mid-century and end-century, regardless of the GHG emissions scenario, is sub-Saharan Africa. Projected impacts on beef production in central America are also consistently high, although the dairy sector is projected to be less at risk in terms of the percentage of early-century production lost.

	Milk production losses	Beef production losses	Total
2045			
SSP1-2.6	3·24 (0·7%)	21·75 (0·8%)	25·00 (0·8%)
SSP5-8.5	4·33 (0·9%)	29·00 (1·0%)	33·33 (1·0%)
2085			
SSP1-2.6	3·32 (0·7%)	22·11 (0·8%)	25·43 (0·8%)
SSP5-8.5	9·06 (1·9%)	58·92 (2·1%)	67·98 (2·0%)

Data are methane emissions mitigated in Mt CO_2 equivalent (% of total enteric fermentation emissions produced as a result of feeding the global dairy and beef herds).

Table 3: **Global methane emissions mitigated due to reduced dry matter intake in Mt CO_2 equivalent**

	Milk production	Beef production	Total
2045			
SSP1-2.6	3·26 (1·7%, 2·82–3·69	11·39 (5·3%, 9·79–12·00)	14·65 (3·6%, 12·61–15·69)
SSP5-8.5	4·35 (2·2%, 3·77–4·93)	15·17 (7·1%, 13·05–17·30)	19·52 (4·8%, 16·82–22·23)
2085			
SSP1-2.6	3·34 (1·7%, 2·69–3·78)	11·55 (5·4%, 9·93–13·17)	14·89 (3·7%, 12·62–16·95)
SSP5-8.5	9·14 (4·7%, 7·92–10·36)	30·80 (14·4%, 26·47–35·13)	39·94 (9·8%, 34·39–45·49)

Data are annual value in US$ billion (2005 constant $) of production lost from the effects of reduced dry matter intake on milk and meat production compared with 2005 (% of 2005 global production, 95% CI).

Table 4: **Global impacts of heat stress on cattle production**

Discussion

In all scenarios assessed, heat stress was projected to become a serious challenge in cattle production systems as the current century progresses, leading to decreases in milk and meat production. Our results highlight the potential magnitude and extent of the adaptation efforts that will be necessary in different places to combat the effects of increasing heat stress on cattle.

There are several limitations to our analysis. First, we estimated only the direct impacts of heat stress on DMI and subsequent animal production, and not the indirect impacts on animal reproduction and herd growth. Currently there are no global distribution maps of different breeds and types of cattle. We used the best-available dataset,[18] which maps cattle only as a general class, with no distinction between *Bos indicus* or *Bos taurus* animals, or

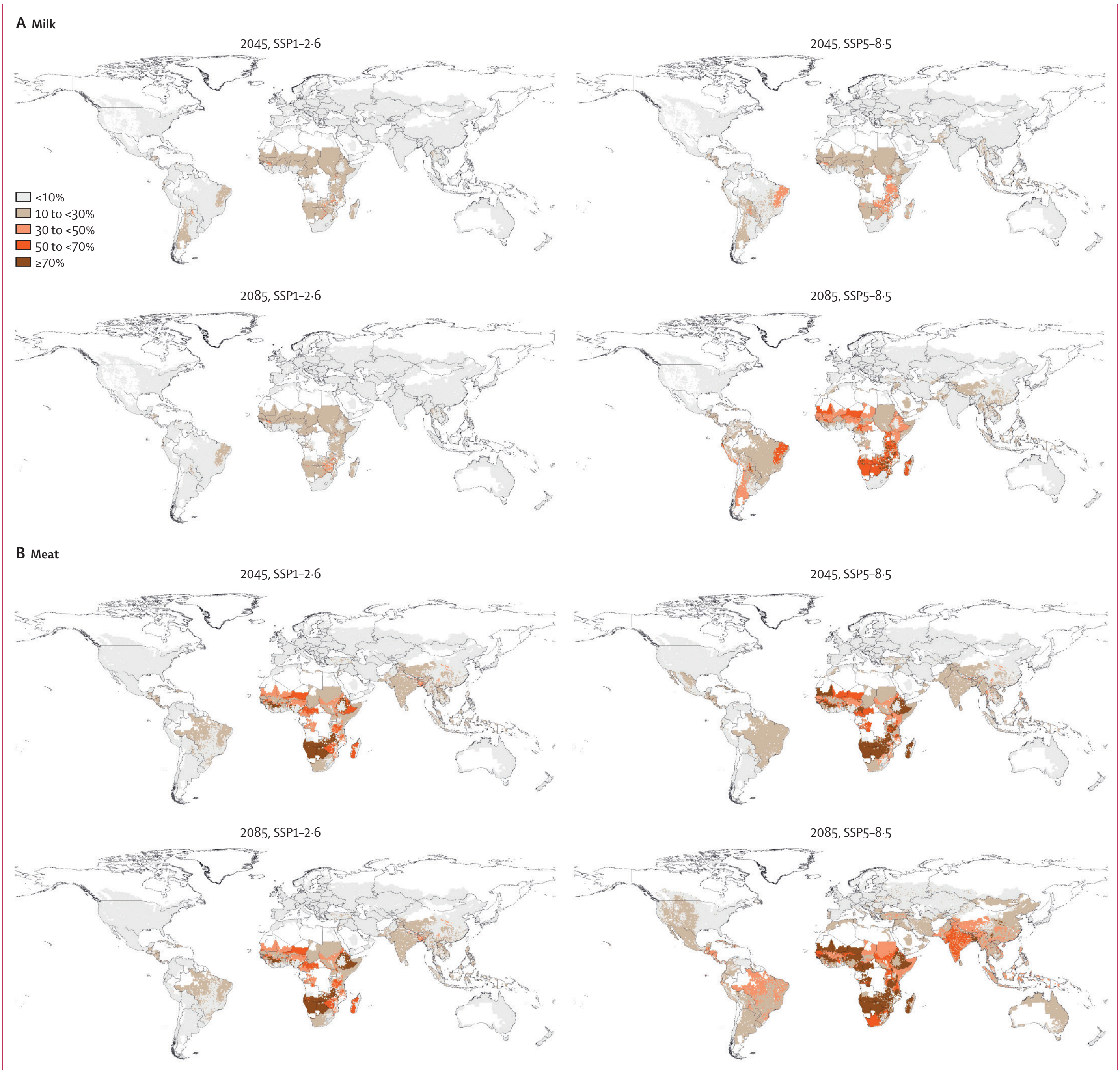

Figure 2: **Country-by-system value of milk production (A) and meat production (B) loss compared with 2005**

between beef and dairy animals. This highlights the value of Herrero and colleagues' dataset,[9] in that published livestock numbers and meat and milk production[22] were consistently harmonised with plausible animal diets at the national level for 2005. Second, we have not considered the indirect impacts of increased heat stress, which is known to modify animal behaviour and can lead to substantial animal suffering, although these effects can be alleviated by the provision of shade, cooling, and ventilation systems.[7] Third, we do not consider changes in the efficiency of utilisation of DMI. Heat stress can reduce rumination and nutrient absorption, although there are no general equations available to quantify this change. Effects of heat stress on feed digestibility are unclear, and heat stress also reduces efficiency of energy utilisation due to higher maintenance energy requirements to alleviate excess heat load.[27,28] These limitations suggest that we are probably underestimating future impacts. Furthermore, global cattle numbers have increased by about 10% between 2005 (our baseline year) and 2019, although most of the increase has occurred in Africa and to a much lesser extent in the Americas and Asia; Europe and Oceania have seen declines in cattle numbers over this period,[22] mostly due to decreased demand.

Despite these limitations, our results highlight the potential magnitude of heat-stress-related production decreases in the future as well as the regions and production systems most at risk. Considerable adaptation will be needed, particularly in tropical cattle production systems, to avoid substantial heat-stress-induced losses in milk and meat production by mid-century, even under a low GHG emission scenario such as SSP1-2.6. Various options are available. Breeding and cross-breeding strategies might be appropriate in some situations. There are significant differences among breeds in ability to cope with heat stress, even among high-yielding genotypes.[29] In higher-income countries, the productive capacity of most domesticated animal species has increased substantially in recent decades, although higher productivity can compromise thermal acclimation and plasticity. Species switching is another alternative, such as switching from cattle to more heat-resistant and drought-resilient camels in pastoral systems of southern Ethiopia.[30] Several relatively low-cost relief strategies are effective and profitable in reducing heat stress impacts, including the use of simple sheds that are well-designed for providing shade, bathing animals several times each day, and installing electric fans in sheds.[31] Different arrangements of shade trees in tree–livestock systems can be highly effective in reducing heat stress.[32] For more intensive cattle production systems in which animals are confined or confined seasonally, there are many alternative cooling, ventilation, and building-design options.[33] In-utero exposure to heat stress might increase heat stress adaptive capacity in later life, although late-gestation heat stress exerts carry-over effects on at least two subsequent generations.[34]

Many of the options to address heat stress might be costly or difficult to implement, given the size of the increases in heat stress projected. Particularly in lower-income countries, some locations will become too hot and humid for animals to thrive. Results here suggest that dairy production systems in several regions will face considerable heat-stress constraints by mid-century. The same challenge faces the pastoral regions of sub-Saharan Africa, which are mostly arid-semiarid systems, and cattle often constitute one of the major assets of pastoralist people. As in many systems in Africa, the role of livestock is heavily conditioned by socioculture rather than economic factors, and effective government policies and well-directed international finance will be needed to address these vulnerabilities. The results presented here are but one step in understanding the magnitude of future heat stress challenges. More nuanced analysis at country or local scale is needed, so that the costs and benefit of different adaptation options can be evaluated and actions targeted appropriately. Cattle breed distribution maps at regional or global scale, as well as maps of beef and dairy animal distribution, would greatly assist such analysis.

The effect of climate change on the health and vulnerability of livestock keepers is a compounding risk: the labour capacity of rural populations under a warming climate is very likely to decrease further, beyond the greater than 5% drop estimated since 2000,[35] as the climate niche for comfortable human habitation changes in the future. Loss of labour capacity could have crucial implications for the vulnerability of individuals relying on subsistence farming and livestock keeping. Indeed, such impacts raise considerable ethical and justice-related considerations concerning the welfare of both the people who raise livestock and the animals themselves.[36] Such considerations need to play an increasing part in policy decisions about how to address the challenges of climate change adaptation,[37] particularly related to heat stress and the welfare of people and animals.

Contributors

PT and MH conceived the study. PT and GN compiled the data and carried out data processing and PT analysed the data. PT and GN verified the data. PT led the writing of the original draft with contributions from GN, DM, and MH. All authors contributed to writing, reviewing, and editing of the manuscript. PT had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Detailed results of the study are available in the appendix. Other data used are available from the authors on request.

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