Global risk of heat stress to cattle under climate change

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Abstract

Livestock comprise the largest mammalian biomass on Earth and contribute to global food security. However, despite numerous case studies reporting heat impacts, the global risk of heat-related stress to livestock from climate change remains unquantified. Here, we conducted a global synthesis of documented heat stress in cattle to identify heat thresholds associated with decreased production and fertility, and increased mortality, and mapped these conditions worldwide for current and future climates. We find that unmitigated climate change will increase the duration of multiple-month heat stress outside the tropics whereas severity will increase most in the tropics and sub-tropics. Our results show that development pathways expanding cattle production into tropical forest regions in South America and Africa will both exacerbate climate change and expose hundreds of millions more cattle to increased heat stress, highlighting the contradiction of pursuing land-use practices that are themselves placed at high risk from resulting future climate hazards.

Livestock comprise by far the largest mammalian biomass on Earth[1] and play a fundamental role in society today, through direct contributions to food security and nutrition, supporting crop production through draught power and manure, as well as supplementing income, providing employment, and fulfilling social or cultural needs[2-4]. With economic growth closely mirroring that of the agricultural sector[5,6], investment in livestock has been touted by many as a solution for reducing extreme poverty and enhancing development[7,8]. As such, agricultural production is expected to double or triple by mid-century in developing regions, which will also see larger increases in livestock as diets shift to include more animal-based protein[9,10]. Originally domesticated in the highlands of Central Anatolia and Western Iran[11], cattle now make up the largest share of livestock globally (FAO[12]; supplementary Figure S1). Furthermore, with beef and dairy products among the most greenhouse gas intensive[13], many development pathways that involve growth in the livestock sector are expected to drive greater anthropogenic climate change[14].

In contrast, how future climate change will affect livestock globally is not well known. This is despite heat stress already being a major problem for animal husbandry, with cost estimates of as much as USD1.7 billion annually for the USA alone, mostly in the dairy industry[15]; and the physiological pathways underlying heat stress being well understood[16,17]. Specifically, higher relative humidity limits a body's ability to dissipate excess heat by evaporation, which compounds the impact of high temperatures, particularly in species such as cattle that sweat to stay cool[18]. An extensive body of case studies on heat stress in livestock exists and has been the subject of review[19], and a small number of studies have projected future heat stress for a specific region[20,21], but there has been no effort to consolidate datasets to project livestock heat stress and associated impacts under current climate and into the future, globally.

Here we synthesize existing studies in order to project current and future heat stress for cattle globally. We used a systematic literature review that identified 1138 studies on heat stress in livestock, of which 327 met our predefined inclusion criteria (see methods). We found the vast majority of studies were about heat stress in cattle (n=225 or 69%) and we restricted our analyses to this species, yielding 97 heat stress thresholds calculated from observed impacts of temperature and humidity on fertility, production (mostly milk yield) and mortality (see Supplementary Table 2). This dataset spans 20 years (1999-2020) and covers 22 countries (Fig. 1a,b). Although different indices have been developed to predict heat stress in livestock[22], the need to use commonly-available weather station data has resulted in variations of one, the temperature-humidity index (THI), being used most frequently. Using THI thresholds from our literature synthesis, we project current heat stress duration and severity at 0.25 degree spatial resolution (c. 25km) globally and, using data from 11 climate models and on future land use, how alternative climate and socio-economic scenarios out to 2100 are projected to mitigate or exacerbate risk of heat stress.

Heat stress thresholds

Peer-reviewed studies quantifying heat stress impacts on cattle fertility, production and mortality are mostly concentrated in temperate climates with high cattle density, particularly Europe and North America, with cattle regions in India, South America and East Africa comparatively understudied (Fig. 1b). Almost all studies used one of several basic temperature-humidity indices[23-26], and base their thresholds for onset of heat stress on those mentioned in a small number of historic publications[23-27].

We find that 95% of THI values reported across studies for the onset of negative heat stress impacts on cattle fertility, production and mortality fell below the frequently cited Livestock Weather Safety Index[27] threshold (THI=74) (Fig. 1c). These thresholds were developed 50 years ago, and variations are still widely used by livestock extension agencies to guide farmers[28,29], as well as by many researchers into heat stress[20,30]. Our synthesis of breakpoints reported in the literature suggests that use of the Livestock Weather Safety Index and other similarly high thresholds may substantially underestimate the onset of heat stress conditions impacting fertility, production and mortality in cattle by an average of around 5 THI units.

Across the studies we reviewed, we find that fertility and production are typically impacted at lower temperature-humidity levels than mortality, with the onset of impacts on fertility reported at a median THI of 67, on production at THI of 69, and on mortality at THI of 69.5 (Fig. 1c,d)—consistent with previous research in the field that has evaluated these multiple impacts simultaneously[31]. Although cattle and farming systems from hotter regions could be expected to be more adapted to heat stress, we found no clear trends in onset thresholds between study regions with differing climates (but we note our sample of studies in the tropics is limited in number; Supplementary Fig. S3). This finding is consistent with research showing limited effectiveness of adaptation to existing heat conditions in other agricultural systems[32], particularly crops[33,34].

Mapping current and future heat stress globally

Combining the median heat stress threshold for production (THI>69) and the current global distribution of cattle, we estimate that 77% of cows are already exposed to climate conditions likely to cause heat stress for ≥30 days each year, with 20% (cattle in the tropics) exposed to heat stress conditions all year round (Fig. 2a). By the end of the century, under a high emissions scenario (SSP5-RCP8.5), these percentages are projected to increase to 90% of cows exposed for ≥30 days each year, and 34% experiencing year-round heat stress.

The projected expansion of heat stress duration is greatest in sub-tropical and temperate regions. Year-round heat stress is projected to expand into southern Brazil, southern Africa, northern India, Australia, and central America (Fig. 2b,c). Increased heat stress durations of multiple months are also projected for parts of southern Europe and the southern United States by the end of the century under a high emissions scenario (Fig. 2c), with emergence of >180 days of heat stress across China, southern Australia and southern Japan (Fig. 2c; Supplementary Fig. S4). Climate model uncertainty indicates a large range in the potential spatial extent of regions exposed to future 2-month heat stress across Eurasia and North America under a high emissions scenario (SSP5-RCP8.5; Supplementary Figure S4).

The severity of heat stress for cattle is also projected to increase with climate change. We quantified severity as the mean amount by which THI values exceed the heat stress threshold for all hot days in a year (that is, days with THI>69). Heat stress severity is currently greatest in the tropics, as well as northern India and Pakistan (Fig. 2d). Tropical regions that already endure year-round heat stress for cattle are projected to also have substantially increased heat stress severity under climate change (Fig. 2e,f). Regions with an average of >10 units over the THI heat stress threshold per hot day are projected to expand across the tropics and into the sub-tropics by the end of the century under a high emissions scenario (Fig. 2f). Although absolute temperature increases are projected to be greater towards the poles, increases in heat stress severity are projected to be greatest in the tropics where THI conditions already exceed the heat stress threshold (Fig. 2g,h). This result adds to previous findings of greater exposure and sensitivity to increased heat stress in tropical regions for other food species, such as fish[35], and projections of greater reductions of crop yield and fisheries catch potential in tropical regions under climate change[36-38]. Together, these suggest the potential for a "perfect storm" of compounding risks to tropical food systems[37].

Aggressive emissions reductions will reduce severity and duration of heat stress in the future. Multiple regions have both high severity of heat stress under current climate, as well as high cattle densities, including: India, Brazil, the Sahel, south-eastern United States, and northern China (Fig. 3a). Holding current cattle densities and spatial distributions constant, for a high emissions scenario the average cow is projected to experience an additional two months of heat stress at a mean severity of 10.1 (± 7.4 s.d.) units over the heat stress threshold. In contrast, adopting a low emissions pathway is projected to reduce this exposure to an increase of only 17 days with a mean severity of 7.6 (± 6.5 s.d.). Excluding regions already enduring year-round heat stress, a low emissions scenario would avoid on average 48 (± 45 s.d.) days of exposure for the average cow. Although the specification of the heat stress threshold influences the projected magnitude of heat stress and the benefits of mitigation, the geography of heat stress is similar for the median fertility, mortality and production thresholds, with even greater heat stress (and avoided heat stress from mitigation) when using the lower THI threshold for onset of fertility impacts (Supplementary Figs S5-S6).

Future pathways of heat risk to cattle

Increases in temperature are a major driver of cattle fertility, production and mortality impacts, but of equal or greater importance for future risk is changes in exposure to heat caused by changes in livestock numbers and the spatial distribution of cattle. For instance, under a future scenario of 'Regional Rivalry' (SSP3-RCP7.0)[39,40] with high population growth in developing regions (see supplementary Figure S7 for region designation), high greenhouse gas emissions, and uneven cooperation for addressing environmental concerns, livestock production is projected to more than double in Latin America and increase by over 500% in Africa (Supplementary Figure S9). Assuming that the share of livestock that is cattle remains high, then cattle numbers will increase substantially in these and other developing regions in Asia. Critically, these are the regions where heat stress will be increasing the most (Fig. 3b). This projected increase in cattle numbers in already heat stressed areas in India, and the expansion of cattle into severe heat stress regions of the Peruvian and Brazilian Amazon and the Congo Basin is projected to increase the exposure of hundreds of millions of cattle to heat stress conditions by the end if the century.

This combination of increasing temperature and changes in the number and location of cattle drives risk across both developed and developing country regions. Africa and Latin America are projected to have the highest increase in risk (around four-fold), followed by Asia and the Organisation for Economic Cooperation and Development (OECD) (that is 37 countries in Europe, North America and Australasia) (Fig. 4a-d). However, the relative contribution to risk from warming or changes in cattle number and location differ strongly among regions. In Asia and Latin America the increase in risk is due almost equally to the increasing heat hazard from warming and increased exposure from greater cattle numbers, whereas in Africa the overwhelming majority of the risk increase is driven by increased cattle numbers and expansion of cattle into heat-stressed regions (Fig. 4e-h).

Given that beef and dairy production are major sources of greenhouse gas emissions[13,14] our results for the 'Regional Rivalry' scenario show the inherent contradiction of pursuing development pathways that exacerbate climate change through land-use practices that are themselves placed at high risk from the resulting climate hazards. This feedback loop between emissions and impacts in the livestock system remains underexplored at the global scale. In contrast, a sustainability scenario (SSP1-RCP2.6)[39,40], with low human population growth, large reductions in greenhouse gas emissions, environmental protections and a shift from economic growth towards a focus on human well-being, is projected to almost completely mitigate the increased risk of heat stress to cattle from climate change, across all regions (Fig. 4a-d); due to both lower global warming and reduced numbers of cattle in agriculture.

Projected impacts of heat stress on milk yields

Livestock exposure to excessive heat results in impacts that range from impaired (re)production— including fertility, milk yield, and growth rate—to increased susceptibility to disease and death[17]. To quantify the projected impacts of increased heat stress on cattle we synthesized 53 published estimates of the relationship between heat stress and milk yield under current climate and used these to project changes in milk yield under alternative future climates. Published studies most frequently reported linearly decreasing fertility, milk quality and milk yields above a particular THI threshold[41-45]. However, we caution that because our systematic review specifically focused on heat stress, some studies reporting nonlinear, hump-shaped response curves of milk yield to temperature may not have been captured in our sample. Therefore, our projections of milk yield changes do not account for mitigation of cold stress that may occur due to warming in colder regions like New Zealand[46]. We also caution that we do not account for increased negative impacts due to cumulative heat stress from consecutive hot days or residual impacts of lower milk yield after hot days[18,45] , and that this may result in an underestimation of impacts in hot regions.

Global milk production is projected to be adversely affected by increased heat stress (Fig. 5). Compared with 2015 levels and holding cattle numbers fixed, annual milk yields are projected to decline by around 35 million tons under a high emissions scenario, but this is reduced to around 22 million tons under a low emissions scenario (Fig. b). Although fractional losses are projected to be highest in Africa (due to low current yields), absolute losses of milk yield are largest in Asia (Fig. 5a,b). However, even without considering future adaptation in our projections, uncertainty among published studies on the magnitude of the heat stress effect on milk yield is greater than uncertainty in climate conditions due to differences among climate model projections to 2050 (Fig. 5b). Given the amount of carbon dioxide already emitted by human actions, some increased global warming is unavoidable and thus, in addition to emissions reductions, adaptation measures will be required to reduce heat-stress-related production losses.

Discussion

Our study underscores the current and increasing threat to cattle posed by climate change. Our literature review indicates that temperature and humidity conditions associated with the onset of fertility, production and mortality impacts frequently occur below widely used thresholds for thermal safety in cattle, and that today around 77% of cattle are exposed to climate conditions likely to cause heat stress for at least one month of the year. The area of the planet exposed to year-round or six-month heat stress conditions for multiple months is projected to increase under all emissions scenarios, with the severity of heat stress increasing most in the topics. However, the proportion of cattle exposed to future heat stress is strongly dependent on future development pathways. In particular, societal choices that expand livestock production and put hundreds of millions more cattle in tropical forest regions are unsustainable, because they worsen climate change, which in turn will expose these cattle to large increases in severe, year-round heat stress. In contrast, steep reductions in greenhouse gas emissions and a shift in consumption to reduced livestock production almost completely mitigates this risk.

Adaptation of livestock farming systems to minimize the impacts of heat stress is currently and will continue to be essential in tropical and subtropical regions. Adaptation options may include a combination of: (i) proactive environmental modifications to reduce heat load and improve heat loss, such as provision of shade, improved ventilation and the use of fogging devices and fans[19,21,31]; (ii) strategies to minimize metabolic heat production such as changes in time of feeding and type of feed[47]; (iii) genetic selection for heat tolerance[45,47]; (iii) seasonal management of calving[21]; and (iv) the selection of more heat-adapted cattle breeds or other livestock species such as goats[48,49], although these come with other trade-offs for production (e.g., lower milk yield[50]).

While heat stress impacts are lower in northern latitudes in general, we did not include cold stress in this study; therefore not accounting for the potential benefits of climate change to cattle at higher latitudes or on the central Asian Steppe. Nevertheless, there is a clear need for future work on heat stress risk projections for cattle under alternative climate change and development pathways considering the efficacy of different adaptation options[21,51], especially in understudied tropical regions. The quantification of avoided economic losses could help justify mitigation actions and inform adaptation investments to deal with sustained risks of heat stress. Our results emphasize that in the absence of transitions to more sustainable production and consumption pathways, increasing demands for livestock protein combined with climate change will undermine the productivity and welfare of hundreds of millions of cattle through being exposed to severe heat stress.

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Methods

Literature search. Using a systematic approach, the titles and abstracts of 1 138 publications mentioning Temperature Humidity Index (THI) and livestock were screened for inclusion in this study using predefined inclusion criteria (see Supplementary Table S1 for detailed search terms and inclusion criteria). THI equations and their sources, details on livestock species and breed, study location, management system, impact category (fertility, production and mortality) and nature of the impacts (that is, regression breakpoints for the onset of heat stress and slope coefficients of the effect of THI), were extracted from 299 papers from the literature search and an additional 29 from citation chaining. Of these papers, 225 were for cattle and these yielded 97 records of heat-stress-related impacts that met our above criteria (Table S2; see Table S3 for detailed impact categories).

Temperature Humidity Index specification synthesis. The temperature-humidity index (THI), which incorporates the effects of relative humidity and environmental temperature, is one of the most extensively applied indices used to determine heat stress in livestock[31,52]. While some work has gone into updating the THI specification by including solar radiation (sometimes as the 'black bulb' temperature) and wind speed[22,53], most ruminant studies used a specification from a landmark paper in 1959[23], originally developed for humans, or from close derivatives[26,54]. Because nearly all included studies used only temperature and humidity, and some studies reported no significant difference between wind and radiation adjusted measures compared with just temperature and humidity[43], we did not include wind and solar radiation in this study. Considerable research has focused on comparing THI specifications to each other, including Gernand et al.[31], who found a greater than 95% correlation between nine different specifications. Unfortunately, some studies utilized the THI formulation from Thom (1959)[23], but did not convert their temperatures in Celsius to Fahrenheit correctly (which the equation was designed for), resulting in THIs and impact thresholds that were not directly comparable to the rest of the studies. For consistency, when comparing across THI thresholds, we converted all specifications to the Thom 1959 specification at 50% relative humidity (RH).

Determining onset of heat stress. Many studies of livestock heat stress use thresholds for onset of heat stress based on those developed in the USA in the 1970s[24,25,27]. Here, we extracted thresholds of onset reported in the literature from studies on heat stress impacts. We classified thresholds by categories of impact (fertility, production and mortality) and calculated the median THI threshold for onset of heat stress impacts in each category. THI values used to determine impacts vary widely, including: daily and monthly mean and maximum THI. However, because daily mean THI values were by far the most commonly reported, we used daily mean THI, which has been shown to be a good indicator of heat stress[55]. We converted daily maximum THI threshold studies based on the mean difference from daily mean and max values based on station weather data (from HadISD v3.1.0.2019f[56]) at the study location. Studies with different THI equations were converted at 25°C and 50% RH. Baseline climate at the study location is taken from HadISD v3.1.0.2019f [56].

Historical THI calculations. Gridded reanalysis hourly temperature and dewpoint temperature are taken from ERA-5[57]. The historical period consists of the 30 years between 1985 and 2014, because these are the last 30 years in the historical simulations in the CMIP-6 conventions. Daily THI mean and maximum values are calculated for each 0.5 degree grid cell using the following equation, where T is the temperature in degrees Celsius, and RH relative humidity in percent:

$$THI = (1.8*T + 32) - [(0.55 - 0.0055 * RH\%) * (1.8 * T - 26)]$$

Equation 1

Relative humidity is converted from dewpoint and temperature using the equation from Stull (2011)[58] and Bolton (1980)[59], and where wet bulb is needed, from Stull et al. (2011)[58]. Historical heat stress duration consists of the number of days above the median THI threshold for the onset of heat stress from the published studies, here for production: 69, fertility: 67, and mortality: 69.5.

Future climate projections. Climate model historical simulations and future projections under the coupled Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) are taken from the CMIP-6 archive[60]. Daily mean near surface temperatures (tas) and specific humidity (huss) are used to calculate daily mean THI using the Thom (1959)[23] specification (Equation 1).

Climate projections were obtained from the following 11 climate models which provide near surface temperature (tas) and specific humidity (huss) at the daily timestep for SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5: KACE-1-0-G, BCC-CSM2-MR, UKESM1-0-LL, CNRM-CM6-1, GFDL-ESM4, CanESM5, CNRM-ESM2-1, EC-Earth3-Veg, MRI-ESM2-0, CESM2-WACCM, MPI-ESM1-2-HR. For the end of century changes in heat stress (Figure 2), we calculated day-of-year median values for each climate model for the period 1985-2014, and for the period 2070-2099 (for each SSP). A day-of-year delta is then calculated for each climate model, upscaled to ERA resolution with a bilinear interpolation, and applied to the historical ERA THI to get the absolute value projection.

For the change in heat stress (Figures 3-5), each climate model is compared to its own baseline without the ERA bias correction. Changes in heat stress at each decade are calculated as the total number of THI units over threshold cumulative across all days for the decade, subtracted by the mean decadal THI units over threshold from the period 1985-2014. This yields a measure of the mean daily increase in THI units over threshold. Each decade consists of the 5 years on either side of the listed year (i.e. 2015 - 2024 is the 2020 value) to align with the SSP data, which is provided at the following year spacings; 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100. Heat stress change projections for 2100 only used the years 2995-2999 because the majority of the CMIP-6 models stop at the end of the century. Changes in heat stress are weighted within a country based on the distribution of cows within the country in the historical record for 2010[61] or on the future projected cattle distributions (next section).

Future cattle increase under the SSPs. Here we focus only on SSP1-RCP2.6 ('Sustainability' scenario)[62] and SSP3-RCP7.0 ('Regional Rivalry' scenario)[63]. We selected these two scenarios as they represent the largest projected divergence in future livestock consumption globally (Supplementary Fig. S9), and also in the expected challenges to climate change mitigation and adaptation. For each SSP we used the so-called marker model scenario for the land use change projections (LUH2[64], see [65] and [66] for more details about model assumptions). So-called 'reforming economies' are ignored.

Future cattle expansion is projected using the following procedure. First, total percent change from 2015 in livestock production is calculated at the regional level based on the Integrated Assessment Models (IAMs) used in the SSP analysis for 2020 (2015-2025), 2030 (2025-2035) and so on to 2090 (IIASA[40]). Next, a total number of cattle is calculated for each region based on 2015 levels from FAOSTAT[12] and the percent change in production projected by the IAM. Cattle are added or removed from individual countries based on those countries' share of change in agricultural land (cropland + pasture + rangeland) from the same baseline IAM model. For example, if Brazil has 30% of Latin America's increase in agricultural land in the year 2050, then Brazil gets 30% of the total increase in cattle in Latin America in that decade. Cattle are added proportionally within the country to the additional agricultural land from the IAM model. We do not account for density variation within a country, or move existing cattle within a country.

Countries with decreasing agricultural land within a region of increasing livestock production are assumed (Asia, Latin America, Middle East + Africa) to have fixed cattle numbers because intensification is increasing in general within the region in future SSPs, (livestock production is outpacing agricultural land expansion in general). For the OECD, a decrease in livestock production is projected for most SSPS. Here we take cattle away from countries proportionally based on share of lost agricultural, mirroring the process. Cattle are proportionally removed within a country from the lost agricultural land.

Milk production impacts. The linear reduction in milk yield per cow per day per unit THI (usually linearly decreasing beyond a breakpoint or threshold) was extracted from the literature. Only studies that reported kg or L per unit THI per day were included for comparability (53 published slope coefficients). The increase in total unit THI over threshold per day was calculated using the same method as previously stated for Figure 3 (without the ERA correction) except the number and location of cattle within a country is held fixed. Dairy cows are assumed to be evenly distributed across all cattle within a country (no analogous dairy-only dataset is available). Average daily increase in THI within a country is applied to average daily milk yield. Baseline milk yield and production data at the country level is taken from FAOSTAT[12].

Data availability

All data used in this analysis are publically available at the following locations:

FAOSTAT: http://www.fao.org/faostat/en/

Cattle densities: http://www.fao.org/livestock-systems/global-distributions/cattle/en/

Land use: https://luh.umd.edu/data.shtml

SSPs: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome

ERA-5:https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview

CMIP-6: https://console.cloud.google.com/marketplace/product/noaa-public/cmip6

Station weather data: https://www.metoffice.gov.uk/hadobs/hadisd/index.html

THI thresholds and impacts: These data will be uploaded to the Dryad data repository before publication.

Code availability

All code used in this analysis is available from the authors upon request.

Acknowledgements

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Author contributions

C.H.T., M.A.N., and J.A.F. conceived the research. M.A.N. and B.O. performed the literature review. J.A.F. prepared the figures. J.A.F performed the analysis with input from all authors. C.H.T. wrote the first draft of the manuscript and all authors contributed to subsequent revisions.

Competing interests

The authors declare no competing interests.

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Figures

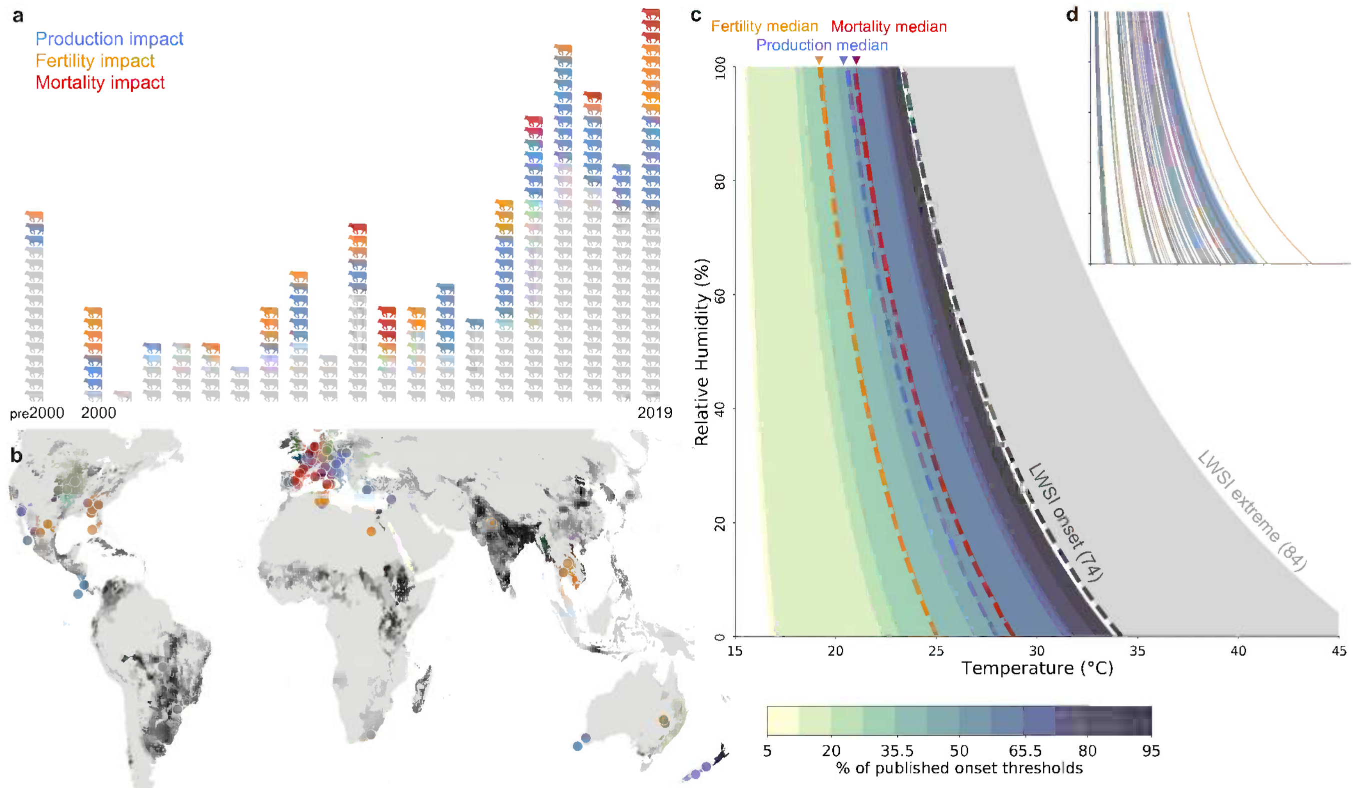

Figure 1 | Heat stress studies and validated thresholds for cattle. a, Temporal distribution of literature included in the systematic review of heat stress for cattle (each icon is a single study or observational threshold with gray indicating those studies that did not meet the data inclusion criteria). **b**, Distribution of study locations globally with cattle distribution density shown in grey from FAO for 2010[61]. **c**, Distribution of 97 observed thresholds of the temperature-humidity index (THI) for the onset of heat stress in cattle. The blue-green colour scale shows the percent of published temperature-humidity thresholds for the onset of impacts, using the THI equation from Thom 1959 (see Methods). Dashed lines show the median of published impact onset thresholds for production, fertility and mortality. Almost all published studies indicate onset of heat stress in cattle at temperature-humidity conditions well below widely-cited onset values used to guide cattle farmers and heat stress projections (e.g., Livestock Weather Safety Index (LWSI)[27]). **d**, THI thresholds from individual studies, coloured by impact type (production, fertility, and mortality). See Supplementary Figs S2-S3 for distribution of thresholds by local climate and impact type in a larger panel.

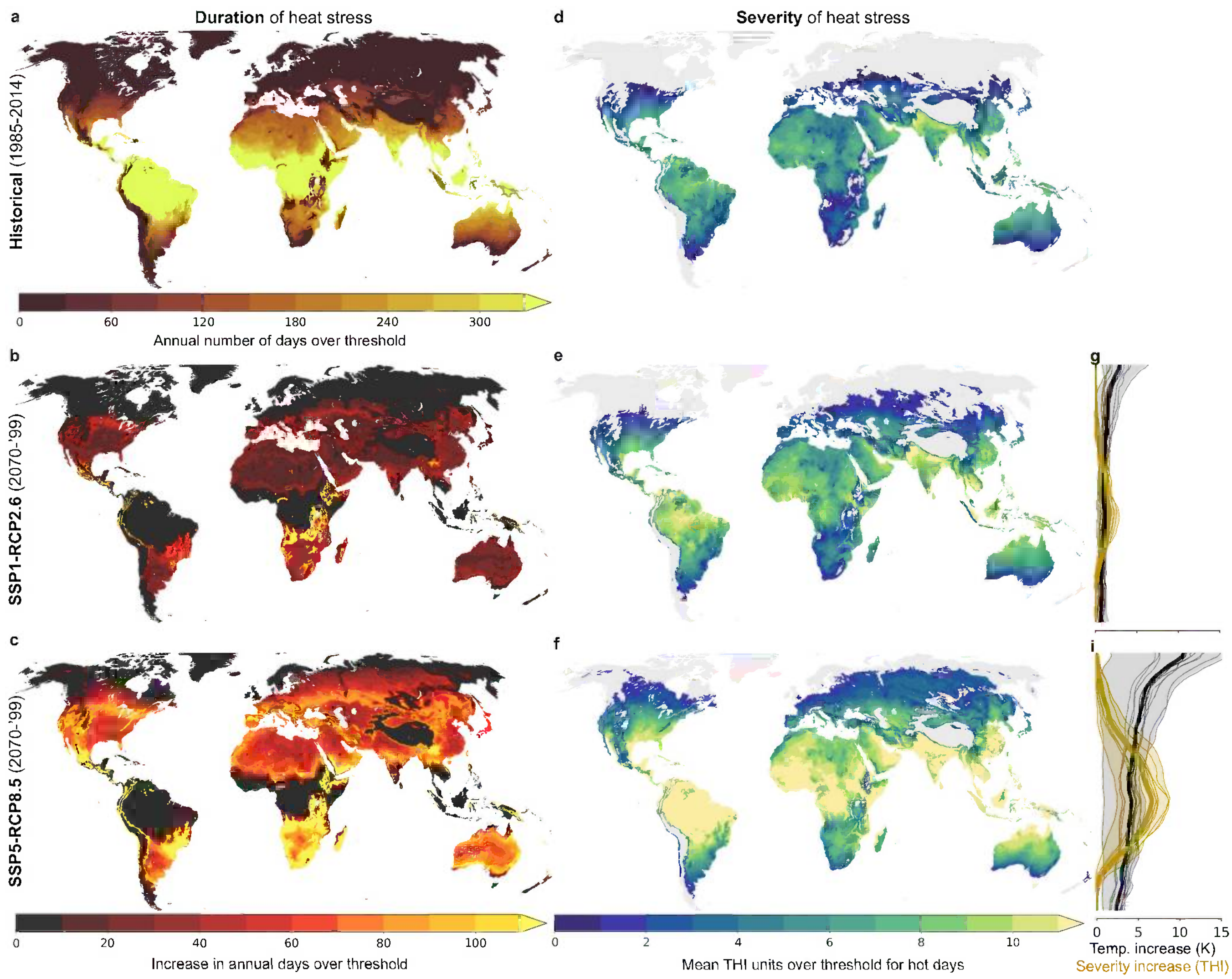

Figure 2 | Climate hazards for cattle under current and future climates. a–c, duration and **d–e** severity of heat stress for cattle under historical and alternative future climates. **a**, Mean number of days per year under historical climate (1985-2014) that were above the threshold for heat stress impacts on production (THI>69). **b–c**, Mean increase in the number of days per year above this threshold at the end of the century under low (SSP1-RCP2.6) and high (SSP5-RCP8.5) greenhouse gas emissions scenarios. **d–f**, Mean exceedance of threshold on days that are above the heat stress THI threshold. **g–i**, Latitudinal mean of the increase in daily temperatures over land (black) and of increase in mean units of THI exceeding the threshold for hot days (gold). Historical climate data were from ERA-5 and future projections from 11 CMIP-6 models (see Methods). Note: light gray areas panels **d–f** have no days above threshold. See Supplementary Figs S5-S6 for maps made using fertility and mortality THI thresholds.

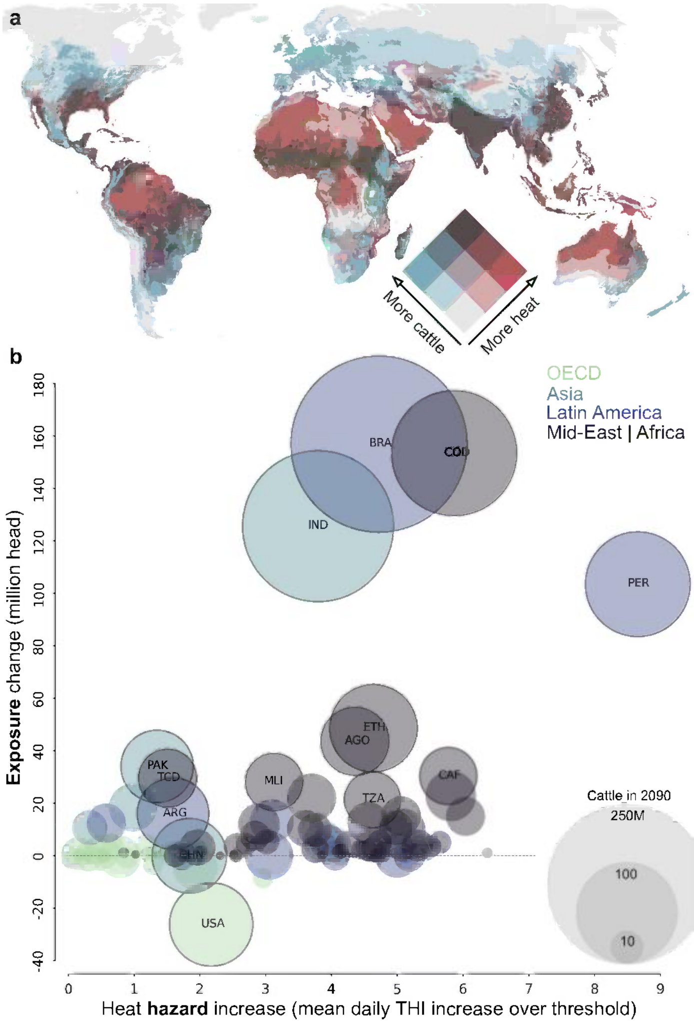

Figure 3 | Historical climate risk to cattle and future climate hazards and exposure. a, Historical climate risk: bivariate map showing historical yearly heat stress severity intersecting with historical cattle densities from FAO[61]. **b**, The increase in exposure (the number of cattle) and projected heat stress hazard (increase mean daily THI units over threshold compared to the 1985-2014 baseline) at the country level under the 'Regional Rivalry' scenario (SSP3-RCP7.0) for 2090 (see Methods). Bubble size is the number of cattle in each country in the year 2090. Countries with more than 30 million cattle in 2090 are labeled with their ISO codes. See Supplementary Figure S10 for projected country-level cattle increases across the century, and Figure S11 for how heat hazards and exposure progress from 2030 to 2090.

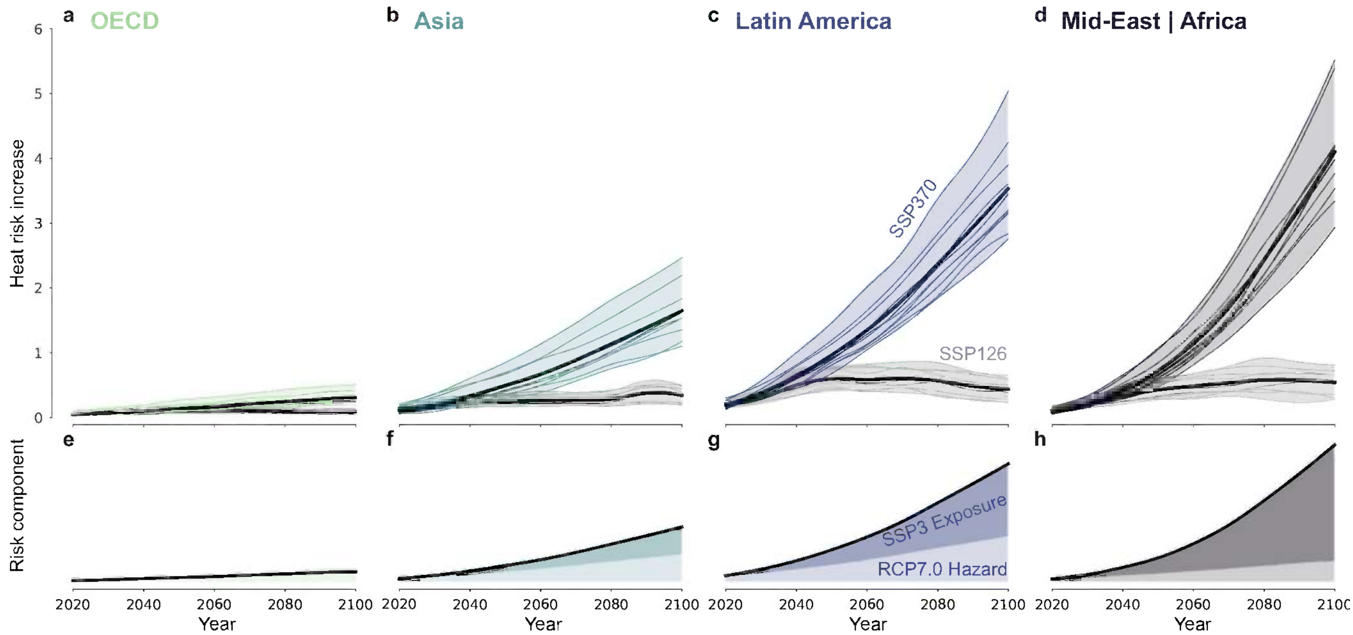

Figure 4 | Potential increases in heat risk to cattle in the 21st century. a–d, Heat risk increase (combined hazard and exposure) for cattle by region for a high emissions, low environmental protection scenario with large increases in cattle production (SSP3-RCP7.0; colours) and a low emissions, high environmental protection scenario with low increases in cattle production (SSP1-RCP2.6; grey). Heat risk increase on the y-axis represents the number of cattle multiplied by the increase in total THI units over the heat stress threshold in each year (units are billion-head-THI increase). Individual lines are individual climate models and thick black lines are the ensemble means. **e–h,** Relative proportion of risk increase due to changes in climate (hazard) versus changes in cattle production (exposure) for SSP3-RCP7.0. Light shading in **e-f** indicates relative risk increase with cattle numbers held fixed at 2015 levels.

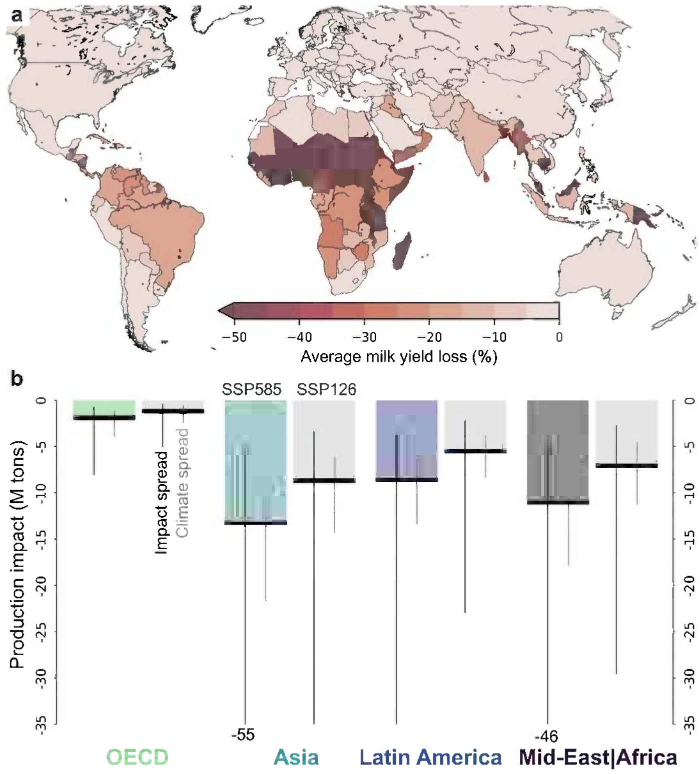

Figure 5 | Heat stress impact on milk production by 2050 without adaptation. a, Percentage change in milk yield at 2050 at the country level under a high greenhouse gas emissions scenario (SSP5-RCP8.5). Losses are projected relative to country-level milk yield from FAOSTAT[12] for 2015 using the CMIP-6 ensemble median and the median of the regression slopes from 53 published studies of heat stress impacts on milk yield. **b**, Absolute change in milk production (millions of tons) compared with 2015 production levels and with 2015 cattle numbers held fixed. Black lines show the mean production loss projected for each region under a high emissions (SSP5-RCP8.5) versus a low emissions (SSP1-RCP2.6) climate. Vertical lines show the range of uncertainty in projected losses due to uncertainty in the relationship between heat stress and milk yield loss (5-95th percentile of impact coefficients of published studies) and uncertainty in projections of future climate (the mean impact coefficient with 11 different global climate models).

Supplement to: *Global risk of heat stress to cattle under climate change*

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Contents

Table S1. | Search string and screening criteria for systematic review

Search string Web of Science Core Collection* (2020-02-27) (n=1 138)	TOPIC: (livestock OR ruminant OR cattle OR cow OR bovine OR "bos taurus" OR "bos indicus" OR dairy OR beef OR camel OR sheep OR ovine OR mutton OR lamb OR goat OR caprine OR "small stock" OR pig OR pork OR swine OR porcine OR poultry OR chicken OR broiler OR layer) AND TOPIC: ("temperature-humidity index" OR "temperature humidity index" OR THI) Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, ESCI
Included if: (n=322, only found 307)	THI one of main aims of the study: ● Focus on verifying or improving the THI equation ● Verifying THI thresholds ● Quantification of the impacts of increasing THI on production outcomes
Excluded if: (n=816)	● Unrelated to THI ● Non-livestock species ● THI only incidentally mentioned in relation to testing feed supplementation or other management changes. ● Impacts not related to production, fertility or mortality

* includes the following databases: Science Citation Index Expanded (SCI-EXPANDED)—1962-present, Social Sciences Citation Index (SSCI)—1962-present, Arts & Humanities Citation Index (A&HCI)—1975-present, and Emerging Sources Citation Index (ESCI)—2015-present, for the University of Cape Town, February 2020

Table S2 | Literature search results. Summary of the literature identified via systematic review and citation chaining, and the inclusion of different livestock species as topics of study.

Species	Systematic review (*n*)	Citation chaining (*n*)	Total (*n*)	Total (%)
buffalo	13	2	15	5%
cattle	208	17	225	69%
chickens	14	4	18	6%
pigs	18	2	20	6%
small stock	40	3	43	13%
multi	6		6	2%
total	299	28	327	

* one citation chaining study was about people (Thom 1959)

Table S3 | Number of reported thresholds for different impact types for cattle

Impact	Impact Detail	Number of impacts	Grouped total number of impacts
Mortality	Mortality	10	10
Fertility	Pregnancy loss	1	26
	Conception rate	12	
	Days open	1	
	Number of daily inseminations per herd cow	2	
	Pregnancy per AI	1	
	Fertility- not specified	3	
	Nonreturn rate	5	
	Pregnancy loss	1	
Production	Average daily gain	2	61
	Birth weight	1	
	Milk fat	2	
	Milk protein	2	
	Milk yield	53	
	Weaning weight	1	
Total number of impacts used in the analysis of breakpoints		**97**	

Table S4 | FAO Livestock Unit (LSU) conversions between different types of animals. Table from: http://fenixservices.fao.org/faostat/static/documents/EK/EK_e.pdf. More details can be found at source.

	Livestock Types**									
Region	**CT**	**BF**	**SH**	**GT**	**PG**	**AS**	**HS**	**MS**	**CM**	**CH**
North America	1	---	0.15	0.1	0.25	0.5	0.8	0.6	---	0.01
Caribbean	0.6	0.6	0.1	0.1	0.2	0.5	0.65	0.6	---	0.01
South Asia	0.5	0.5	0.1	0.1	0.2	0.5	0.65	0.6	---	0.01
Near East and North Africa	0.7	0.7	0.1	0.1	0.2	0.5	0.4	0.6	0.75	0.01
East and South East Asia	0.65	0.7	0.1	0.1	0.25	0.5	0.65	0.6	0.8	0.01
Transition Markets	0.6	0.7	0.1	0.1	0.25	0.5	0.65	0.6	---	0.01
Africa South of Sahara	0.5	---	0.1	0.1	0.2	0.3	0.5	0.6	0.7	0.01
Central America	0.7	---	0.1	0.1	0.25	0.5	0.5	0.6	---	0.01
South America	0.7	---	0.1	0.1	0.25	0.5	0.65	0.6	---	0.01
OECD	0.9	0.7	0.1	0.1	0.25	0.5	0.65	0.6	0.9	0.01
Other	0.6	0.6	0.1	0.1	0.2	0.5	0.65	0.6	---	0.01
South Africa	0.7	---	0.1	0.1	0.2	0.5	0.65	0.6	---	0.01
Near East	0.55	0.6	0.1	0.1	0.25	0.5	0.56	0.6	0.7	0.01

*FAO, 2011; **CT=Cattle; BF = Buffalo; SH = Sheep; GT = Goats; PG = Pigs; AS = Asses; MS = Mules; CM = Camels; CH = Chickens

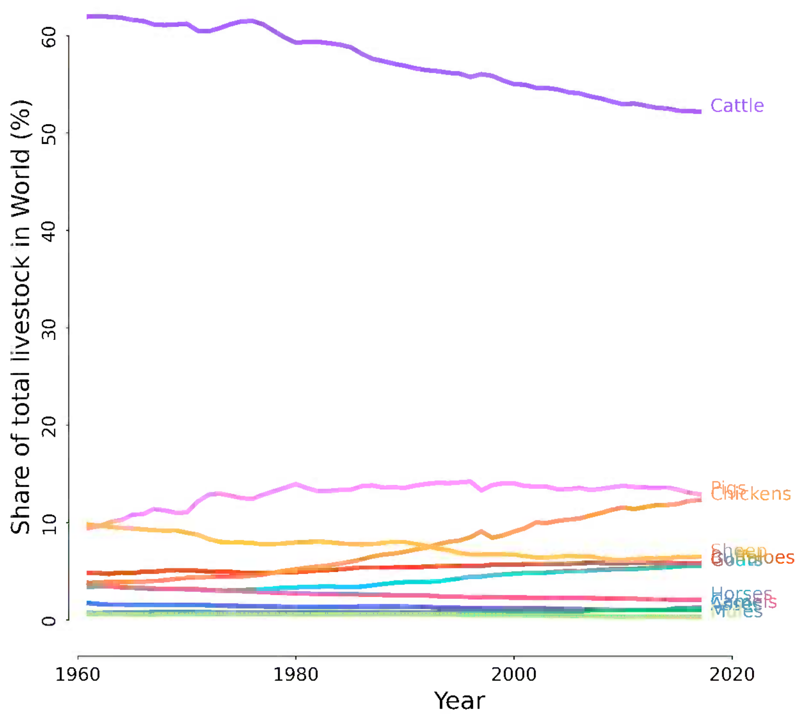

Figure S1 | Share of global livestock by type. Data from FAO livestock patterns (FAOSTAT[1]). Livestock units are calculated by the FAO at the regional scale to account for differences across livestock types. For example, 1 cow in North America is equal to 2 cows in South Asia and 100 chickens anywhere. See XXX for more information. Regional Livestock units (LSU) from the FAO can be seen in Supplemental Table S4.

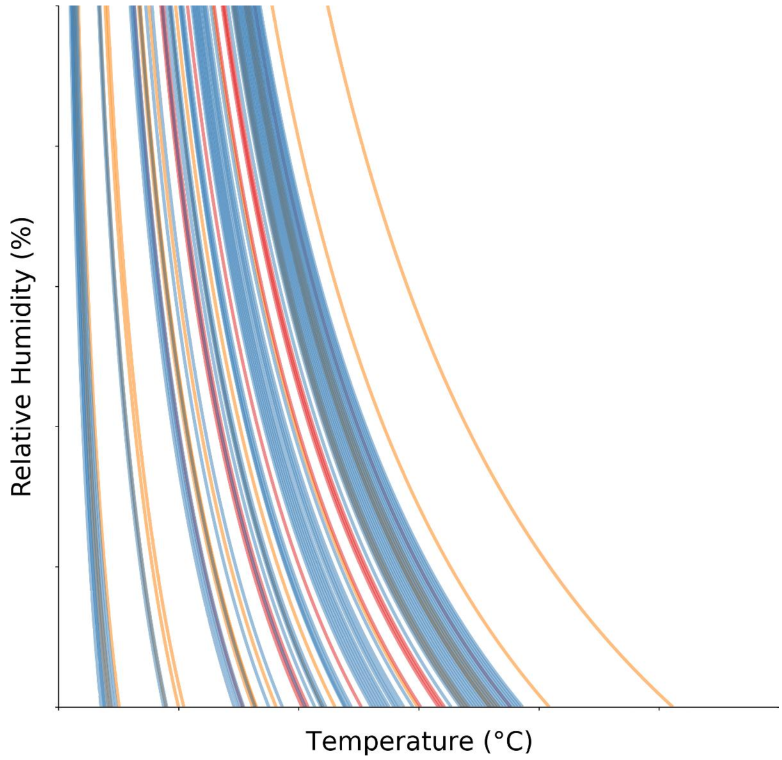

Figure S2 | Impact thresholds by impact type. Distribution of 97 observed thresholds of the temperature-humidity index (THI) for the onset of heat stress in cattle. Lines show the onset of heat stress thresholds for production (blue), fertility (yellow), and production (red). This figure is the same as Fig. 2d in the main text, but is enlarged here for clarity.

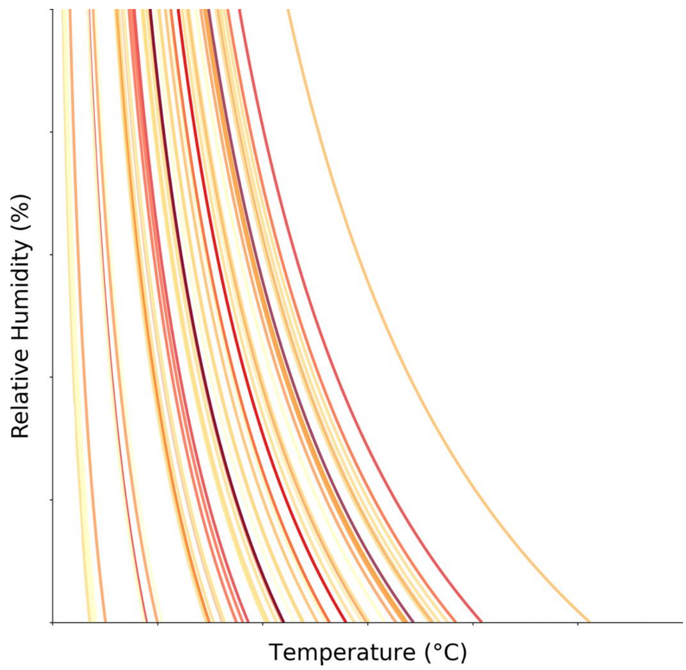

Figure S3 | Impact thresholds by baseline climate. Distribution of 97 observed thresholds of the temperature-humidity index (THI) for the onset of heat stress in cattle. Lines are coloured by mean THI in the study location. Yellow is cooler and red is warmer baseline THI at the study location. No obvious pattern exists. Sampling is between baselines of 40 and 80 THI. More studies are needed in the tropics.

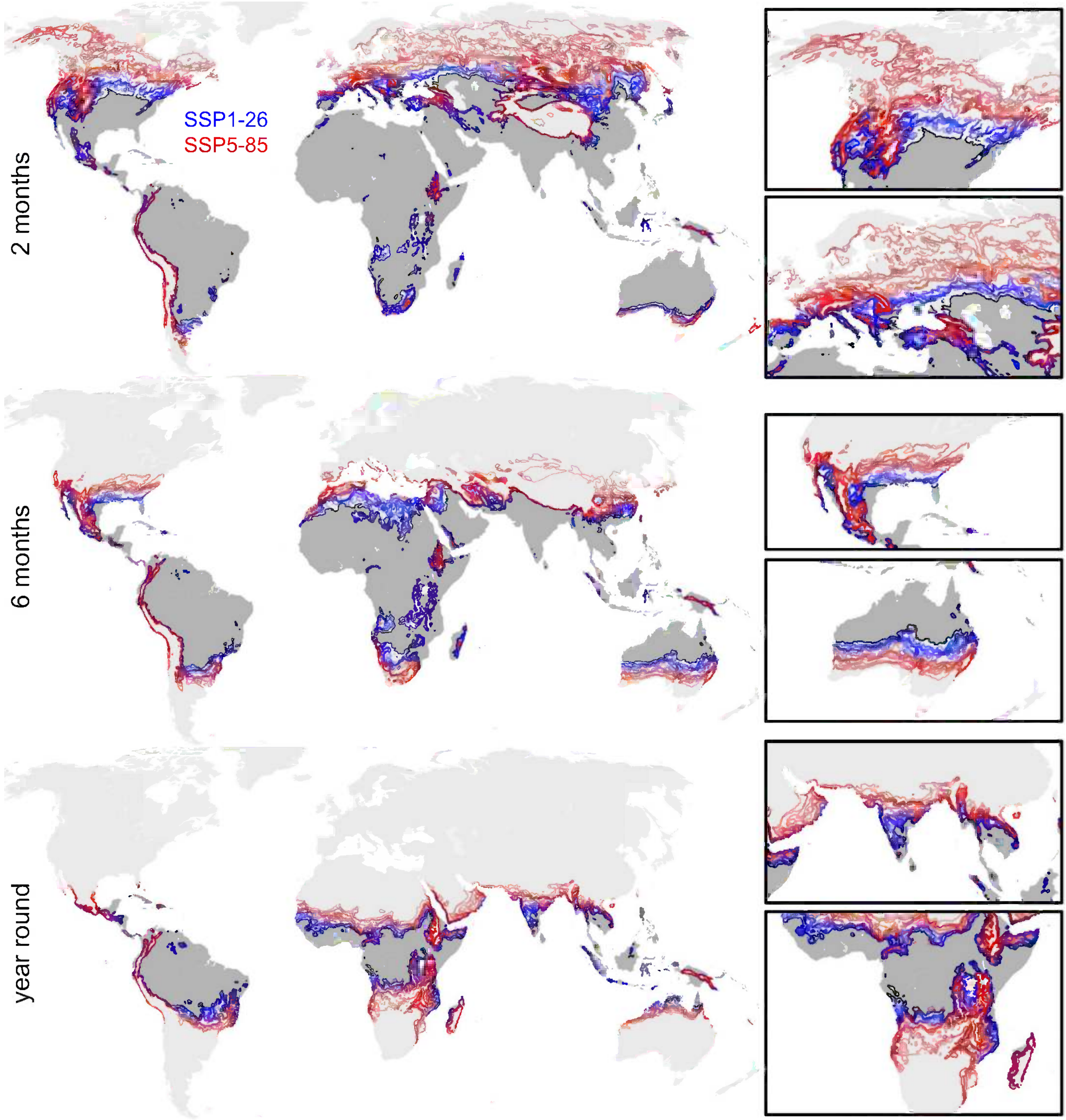

Figure S4 | Poleward progression of the extent of heat stress. Dark gray filled areas illustrate the global spatial extent of the duration of days over the heat stress threshold for three summed totals of days in a year: 2 months (60 days), 6 months (180 days), and all year round. With the exception of year-round heat stress, these time periods are for a total number of days in the year (not necessarily consecutive days of heat stress). Colored contours illustrate the projected expansion of these zones by the end of the century under future climates for a low emissions scenario (SSP1-RCP2.6) and a high emissions scenario (SSP5-RCP8.5) for 11 global climate models. Inset plots zoom in on select interesting areas.

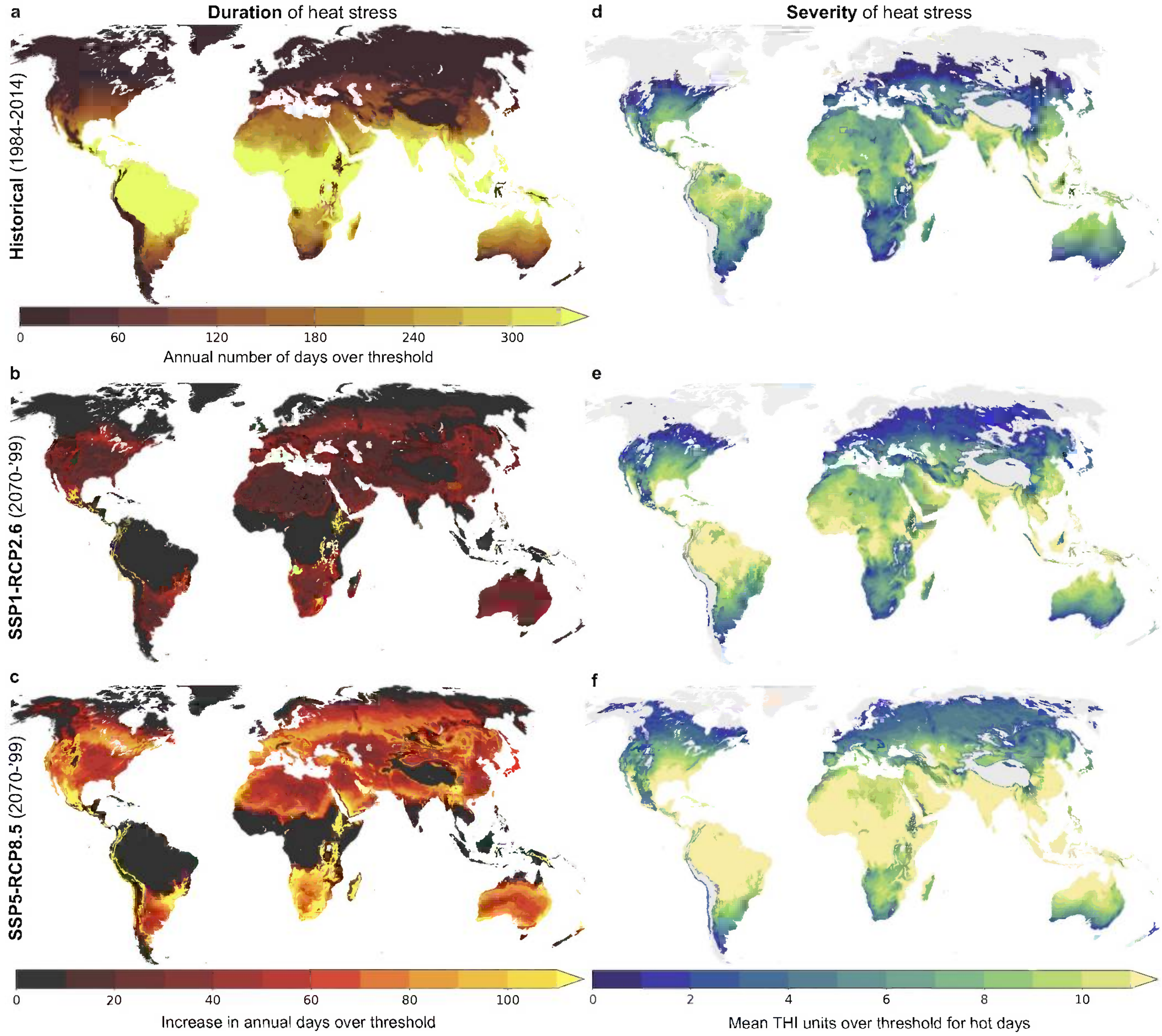

Figure S5 | Climate hazards for cattle under current and future climates based on the median THI threshold for onset of fertility impacts from heat stress. a–c, duration and **d–e** severity of heat stress for cattle under historical and alternative future climates. **a**, Mean number of days per year under historical climate (1985-2014) that were above the threshold for heat stress impacts on fertility (THI>67). **b–c**, Mean increase in the number of days per year above this threshold at the end of the century under low (SSP1-RCP2.6) and high (SSP5-RCP8.5) greenhouse gas emissions scenarios. **d–f**, Mean exceedance of threshold on days that are above the heat stress THI threshold. **g–i**, Latitudinal mean of the increase in daily temperatures over land (black) and of increase in mean units of THI exceeding the threshold for hot days (gold). Historical climate data were from ERA-5 and future projections from 11 CMIP-6 models (see Methods). Note: light gray areas panels d-f have no days above threshold.

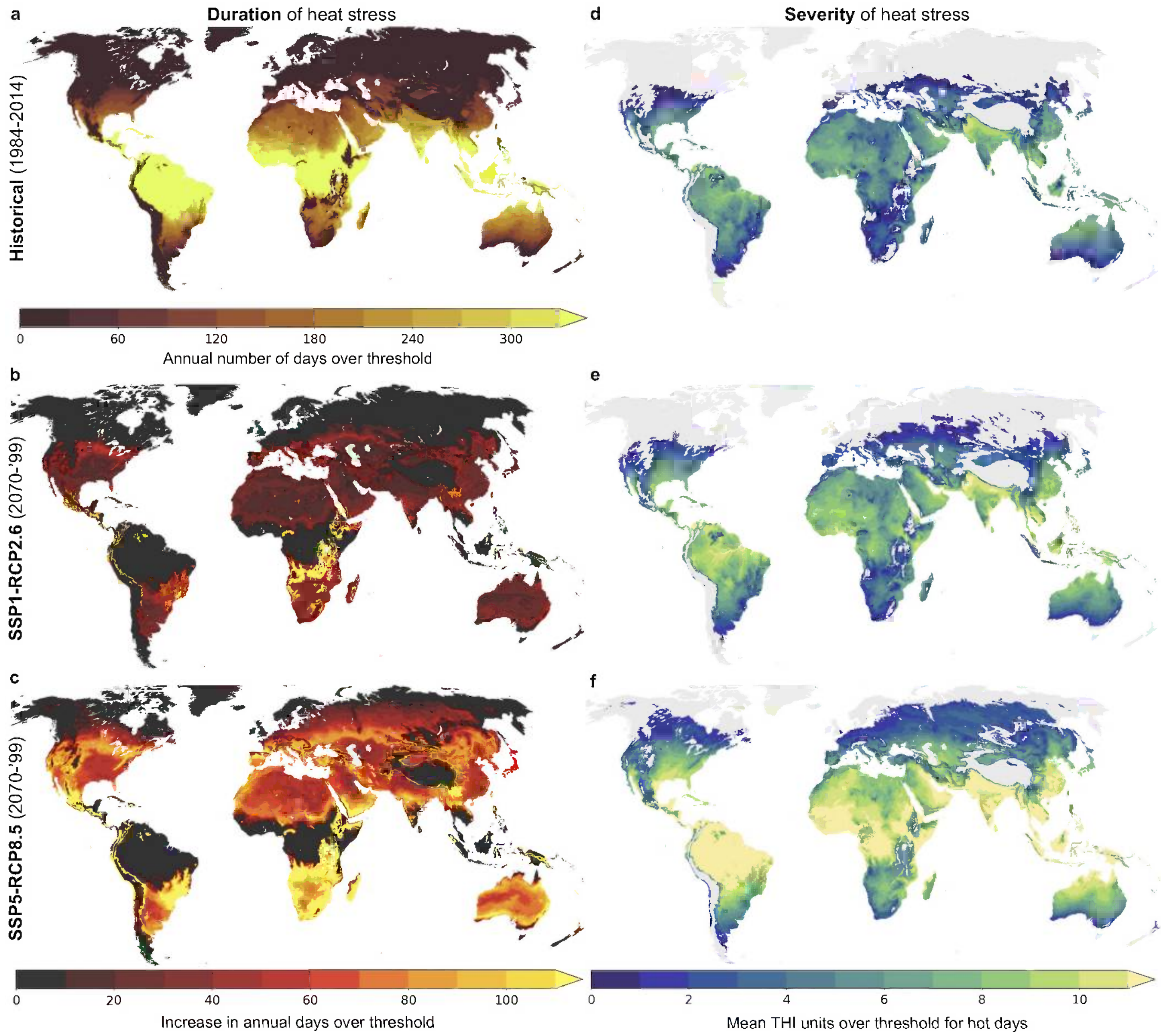

Figure S6 | Climate hazards for cattle under current and future climates based on the median THI threshold for onset of mortality impacts from heat stress. a–c, duration and **d–e** severity of heat stress for cattle under historical and alternative future climates. **a**, Mean number of days per year under historical climate (1985-2014) that were above the threshold for heat stress impacts on mortality (THI>69.5). **b–c**, Mean increase in the number of days per year above this threshold at the end of the century under low (SSP1-RCP2.6) and high (SSP5-RCP8.5) greenhouse gas emissions scenarios. **d–f**, Mean exceedance of threshold on days that are above the heat stress THI threshold. **g–i**, Latitudinal mean of the increase in daily temperatures over land (black) and of increase in mean units of THI exceeding the threshold for hot days (gold). Historical climate data were from ERA-5 and future projections from 11 CMIP-6 models (see Methods). Note: light gray areas panels d-f have no days above threshold.

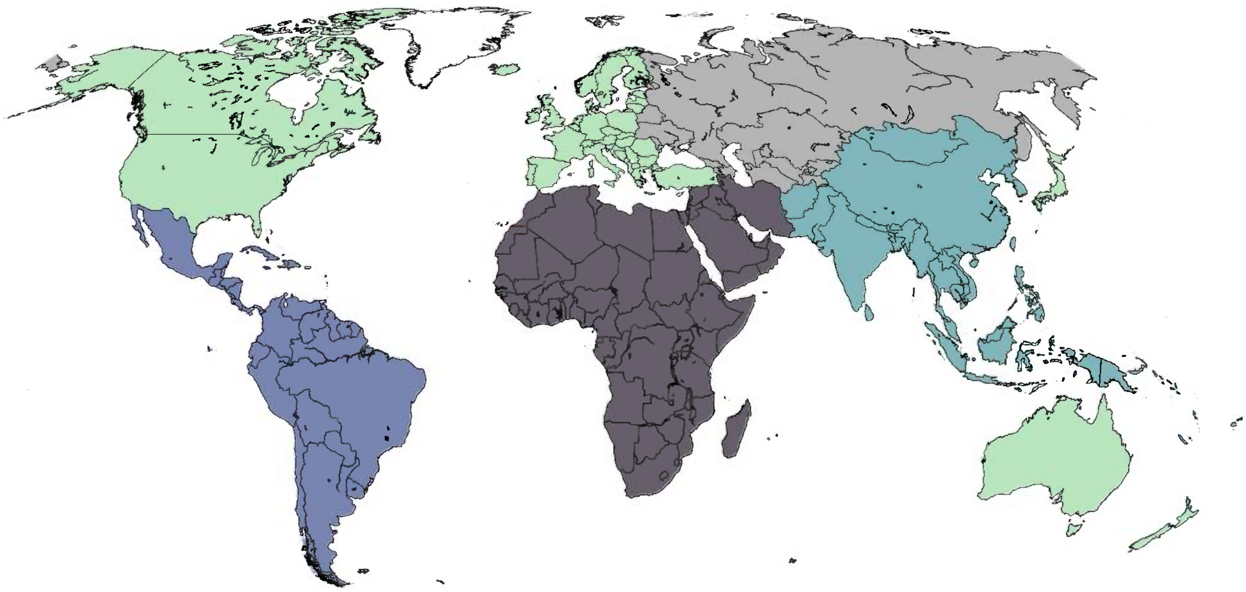

Figure S7 | Region designations used in the analysis. Grey are the so-called reforming economies, and are excluded here.

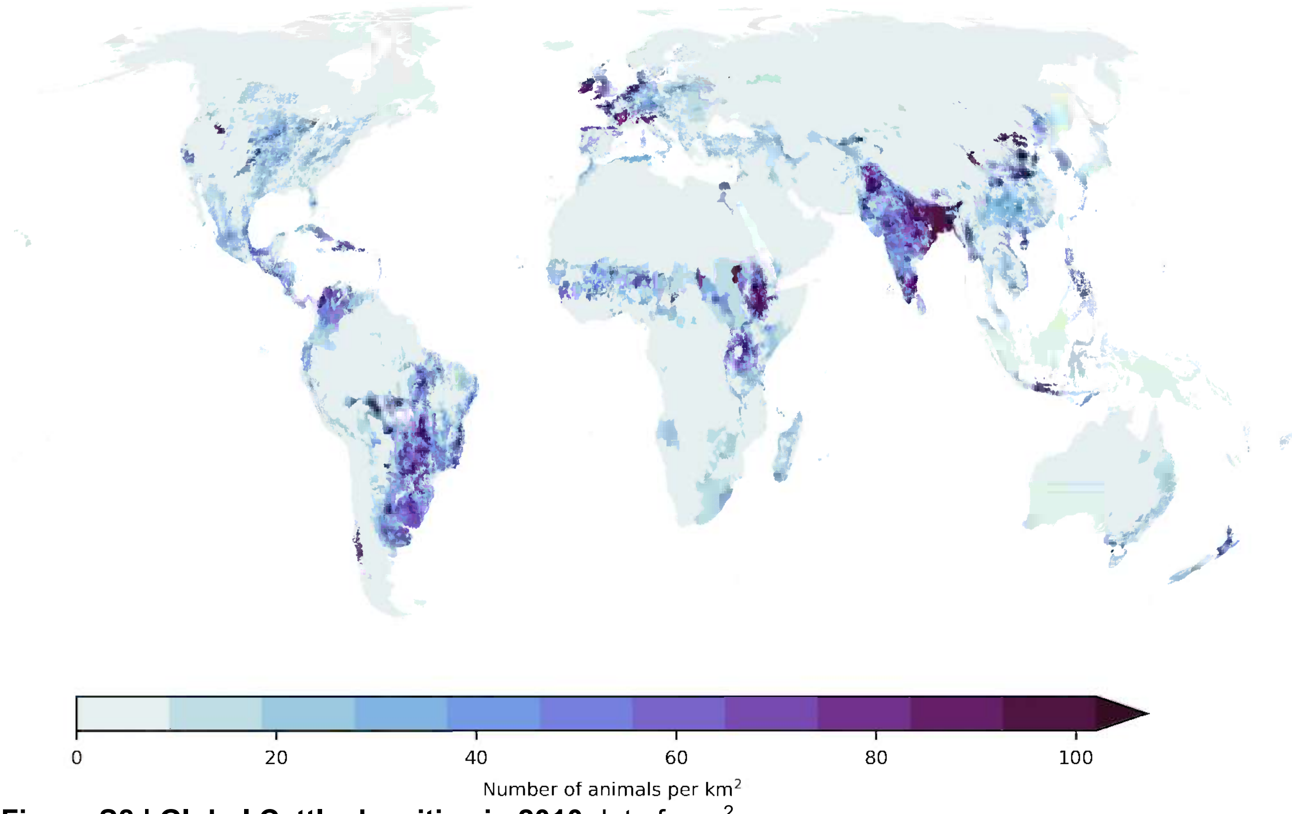

Figure S8 | Global Cattle densities in 2010 data from [2].

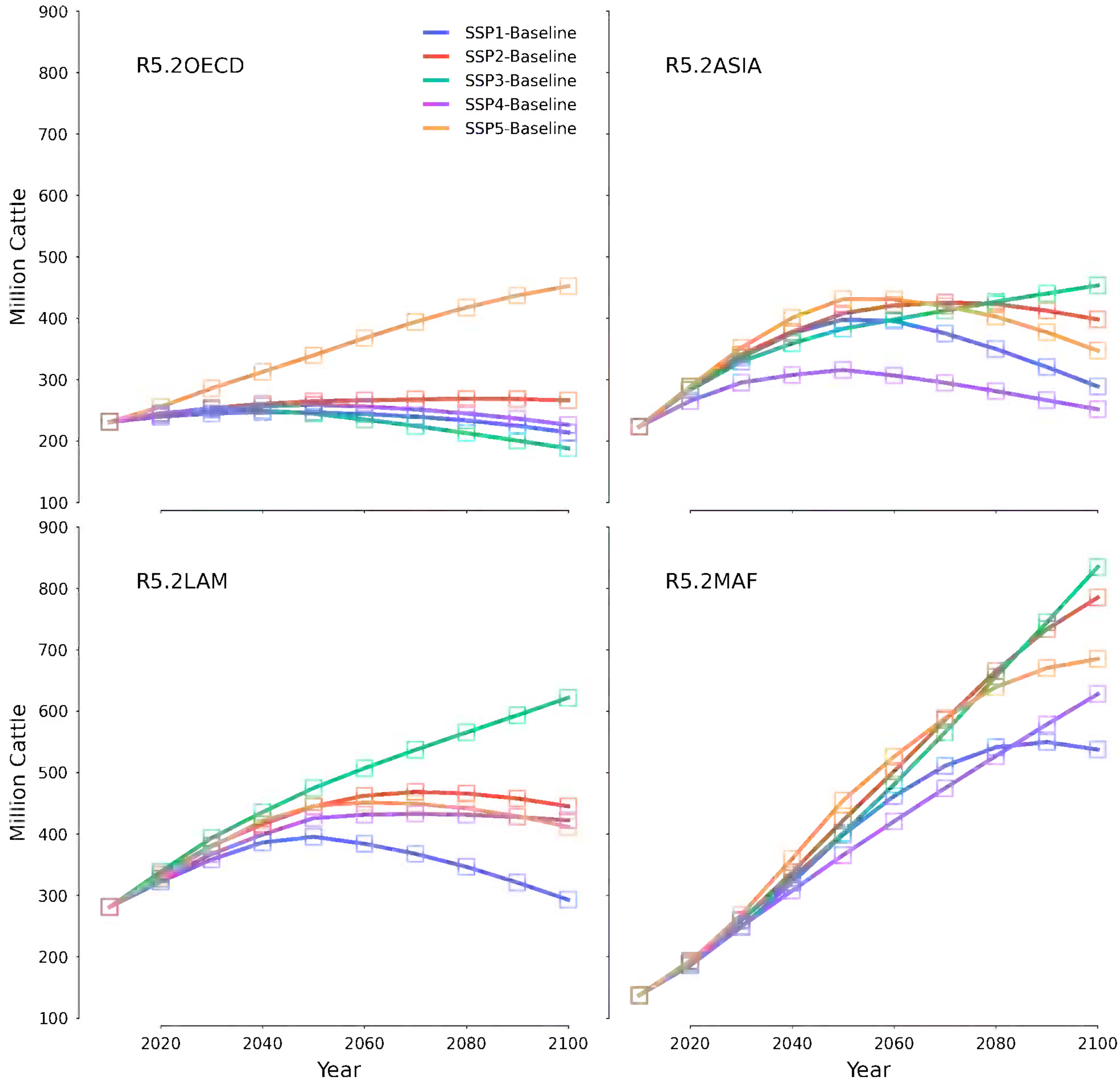

Figure S9 | Number of cattle per region for each of the five Shared Socioeconomic Pathways for the future. Data from IIASA[3] and FAOSTAT[1]. Cattle share is held fixed at current levels in each region. SSP1[4] is 'Sustainability' with low challenges to climate change adaptation and mitigation, SSP2[5] is 'Middle of the Road' with intermediate challenges, SSP3[6]. is 'Regional Rivalry' with high challenges to both climate change mitigation and adaptation, SSP4[7] is 'Inequality' with low challenges to mitigation but high challenges to adaptation, and SSP5[8] is 'Fossil-fueled development' with high challenges to mitigation but low challenges to adaptation. Cattle increases are projected to be greatest in SSP3 and SSP5.

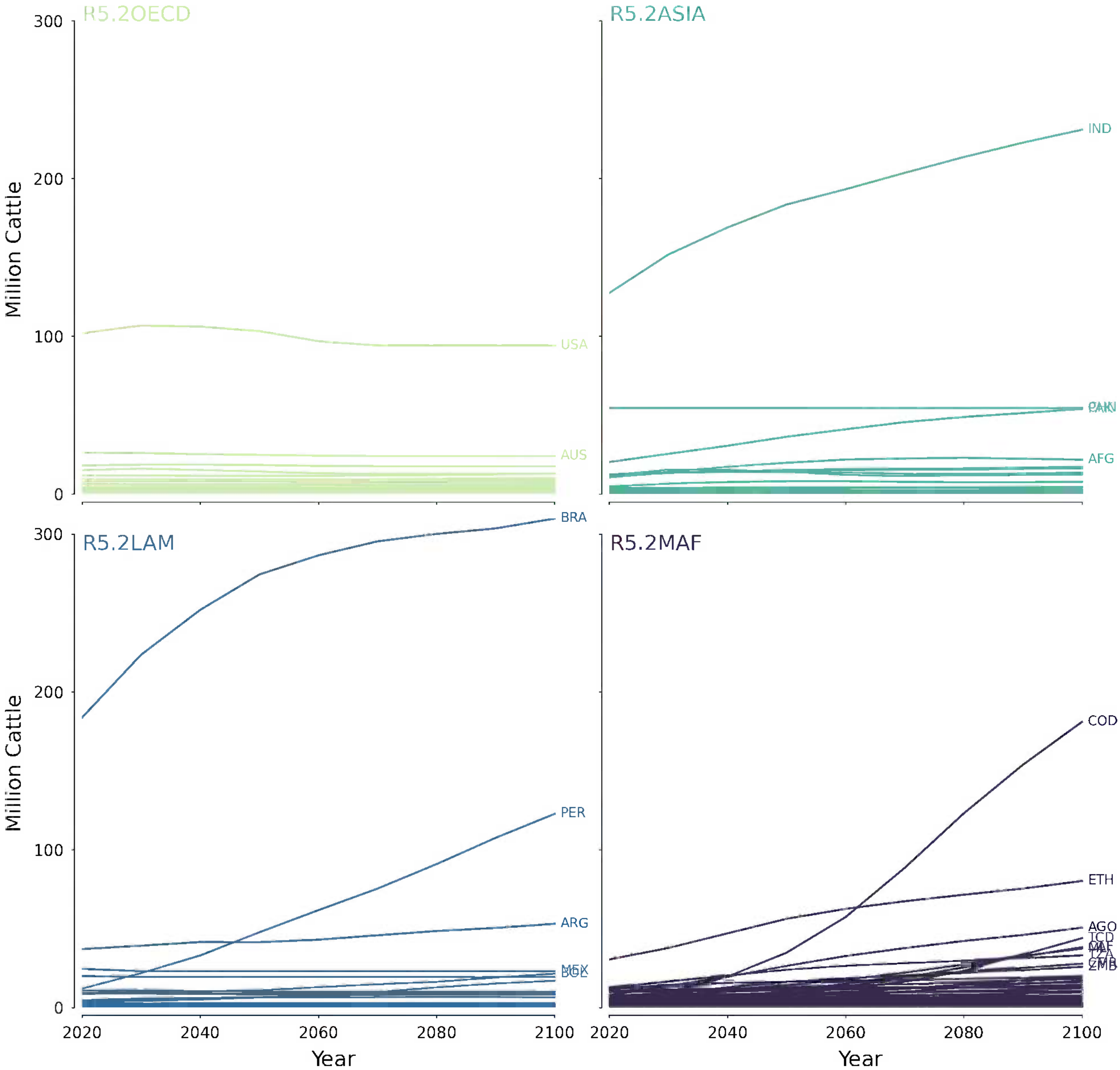

Figure S10 | Number of cattle per country for the 'Regional Rivalry' scenario (SSP3-RCP7.0). Data from IIASA, FAO, and LUH2[9]. Cattle share is held fixed. Cattle are added based on the share of increase in agricultural land at the country level from the AIM model, which is the baseline model for SSP3-RCP7.0. OECD is the Organisation for Economic Cooperation and Development comprising 37 countries in Europe, North America and Australasia.

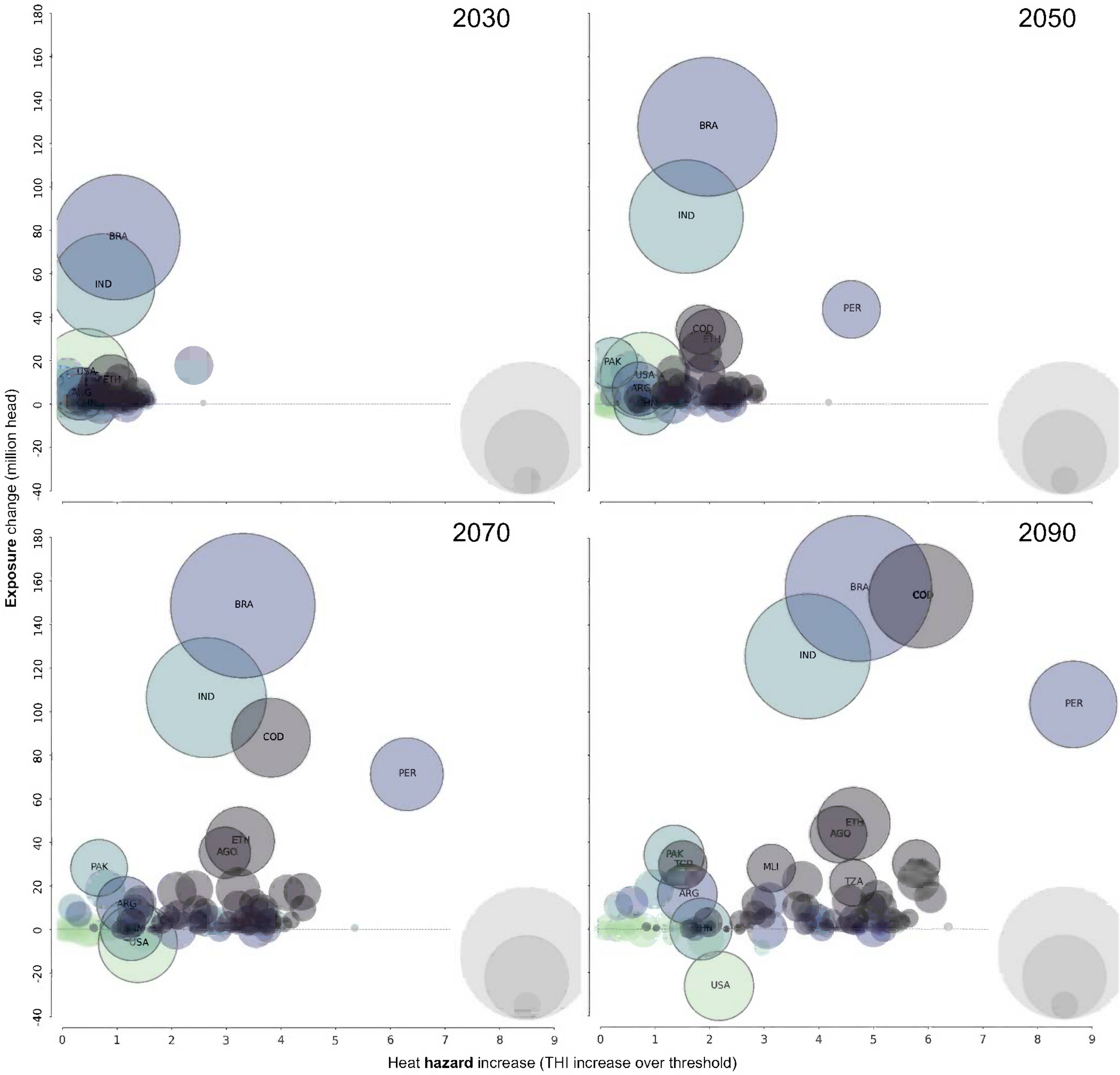

Figure S11 | Projected heat stress hazards and exposure for cattle over time for each country. The increase in the number of cattle (exposure) and in heat stress (the hazard, here increase in days over threshold and increase in severity) at the country level under the 'Regional Rivalry' scenario (SSP3-RCP7.0) in the year 2090 (see Methods). Bubble size is the number of cattle in each country for that decade. Countries with more than 30 million cattle in the decade are labeled with their ISO codes.

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