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Unequal impact of climate warming on meat yields of global cattle farming

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Climate warming affects global livestock productivity. The meat yield from cattle farming (cattle meat per animal) represents livestock productivity at the individual level. However, the impact of warming on cattle meat yield at a global scale is not well understood. In this study, we combine country-level data on the annual meat yield from cattle farming and socio-economic data from 1961 to 2020 with climate projections from General Circulation Models. The findings show that cattle meat yield increases as temperatures rise from low to medium and then decreases when annual average temperatures exceed 7 °C; this repose is pronounced in the grassland-based livestock system. Further, we show that warming creates unequal impacts between high- and low-income countries due to the divergent baseline temperature conditions. Future warming aggravates these unequal burdens between countries, with the most pronounced effects observed under the upper-middle emissions scenario.

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The anthropogenic climate warming is expected to exacerbate the inequality of regional development across the globe. More climate-associated burdens will be undertaken by the poorest and warmest countries because they are likely to emerge as the physiological optimal threshold for both humans[1], agriculture[2], and macroeconomy[3] even undergoing a subtle warming. Moreover, low-income countries cannot afford climate-associated burdens adaptations, which leads to the regions that contribute less to climate warming will experience greater stress[4].

Livestock products contribute over 10% and 30% of global per capita calorie and protein supply, respectively. The livelihood of 400 million people around the world depends on livestock products[5]. Recent studies have emphasized the negative influences of climate change on the livestock system directly through animal health and performance and indirectly through changing the productivity of rangeland or crop feed intake[6,7]. The serious conflict between reduced livestock products supply due to climate change and increased demand caused by population growth seems to be inevitable as a result of anthropogenic greenhouse gas emissions in the present century. Therefore, it is urgent to understand and adapt to the impact of climate warming on livestock production.

Evidence is accumulating that climate warming is reducing the productivity of livestock systems and causing livestock mortality[8]. Animal-level experiments have documented the negative effect of heat stress on animal health by reducing fertility, suppressing their immune systems[9], and increasing the occurrence of disease[10]. Livestock meat yield is a statistic that can be used as a measure for comparing livestock productivity across space and time. Livestock meat yield at a particular place and time is an indicator of feed availability and feed conversion efficiency, which has been inhibited by less eating[11] and faster breathing[12] under a higher temperature condition, which is detrimental to the contribution of energy to production[13,14].

Current knowledge about the response of livestock production to heat stress is limited to the specific species at a regional scale[15]. At the global scale, the potential heat stress exposure is projected to increase and become widespread for nearly all livestock species in most parts of tropical zones by the end of this century[16–19]. At the individual level, the cattle meat yield can indicate the food availability of livestock systems, feed efficiency[20], and greenhouse gas emission intensity[21]. However, the statistical evidence for climate change impacts on global cattle meat yield remains unknown at the global scale.

Here, we fill the gap by providing new evidence for the impact of climate warming on global cattle meat yield with Food and Agricultural Organization (FAO) statistical data. Considering the development across countries is unequal, whether the impact of climate warming on cattle meat yield can become an emerged signal of inequality provides critical guidance for climate change adaptation. We first investigate the response of cattle meat yield to climate change and explore the potential changes in cattle meat yield sensitivity to warming that is regulated by wind and cloud cooling effects. We then quantify the unequal impacts of climate warming on cattle meat yield across countries. Finally, we project the changes in unequal impacts in future warming scenarios.

Results

The nonlinear response of cattle meat yield to warming. As the literature review has found, the preferable temperature range for most domestic livestock is from 10 °C to 30 °C across different species[11], which indicates that warmer and colder climates relative to optimal temperature are both detrimental to livestock, such that we used a quadratic term of temperature to measure the potential nonlinear effect of warming (M1). Considering the heat stress threshold is lower when humidity is higher[22], the temperature and humidity index (THI) is introduced in an alternative regression model (M2) to compare with M1 (Methods). The responses of global cattle meat yield to warming quantified by annual mean temperature, and THI are consistently found to be invert-U quadratic nonlinear. The warming in colder regions, like the Qinghai Tibet Plateau, can boost cattle meat yield[23], whereas in hotter regions, warming reduces cattle meat yield[16]. The marginal effect of 1 °C warming on cattle meat yield is consistently negative (from −0.76% to −0.12%) given by eight regression models (Fig. 1g, Supplementary Tables 1–6). The increase in rainfall and socioeconomic development, like GDP per capita (GPDpc), cereal yield (cerYield), and livestock production index (LPI), can boost cattle meat yield (Table 1).

The wind speed and cloud cover regulate the nonlinear response of cattle meat yield to warming. The estimated optimal temperature or THI thresholds by considering the regulation of wind and cloud cover are greater than those estimated without wind and cloud cover (Fig. 1a, b), which indicates heavy wind and large cloud cover mitigate the negative effect of heat stress on cattle meat yield through slowing down the cattle breath[12] and enhancing the evapotranspiration latent cooling[24]. The cooling effect of wind and cloud cover can be supported by the ratio of sensible and latent heat transfer (Bowen ratio). The larger fraction of cloud cover can inhibit solar energy from reaching the land surface, which reduces the sensible heat transfer, which is shown by a negative dependence of the Bowen ratio associated with cloud cover (Fig. 1c). Similarly, wind can accelerate the evapotranspiration from both land and animal skin, such that the proportion of latent heat transfer is increased by heavy wind, which can be demonstrated by the negative correlation between the Bowen ratio and wind speed (Fig. 1d). A smaller Bowen ratio indicates cooling climate conditions[25]. When experiencing cooler weather, the heat stress on animal performance will be alleviated. Animals prefer to eat more, and the accumulated protein will not be reduced by heat stress, such that the cattle meat yield tends to increase[11].

The cattle in rangeland are directly exposed to heat or cold stress without any preventions, and grassland vegetation is more vulnerable than crops because of the lack of management. We split the grassland-based livestock system from other livestock systems by using the FAO livestock system classification[5], and establish regressions separately. We find greater sensitivity to warming in grassland-based livestock systems than others (Fig. 1e, f, Supplementary Table 9). To check the robustness of greater meat yield sensitivity to warming in a grassland-based system, we used other two approaches to split the grassland-based system (Methods) and find the same pattern (Fig. 2, Supplementary Tables 7 and 8). The lack of management practices determines the greater sensitivity to warming in grassland-based systems because some indoor alleviations, like shed shade, shower, and house heating control[26,27], cannot be applied. In addition, compared with the cropland-feed system, the rangeland vegetation productivity is also more sensitive to climate change[28–31] because of the lack of irrigation and purchasing forage in advance[32]. The irrigation for the cropland-feed system can enable crop water demand to be filled even under drier conditions, such that the supply of animal forage in the cropland-feed system can be sufficient. Also, irrigation for cropland-feed systems can cool the local weather through transpiration, and simultaneously moderate compound hot-dry stress[33]. To check the robustness of the climate warming impact on cattle meat yield, we used eight regression models (Methods) and estimated a similar marginal effect of 1 °C warming on cattle meat yield (Fig. 1g).

Unequal impacts of warming on cattle meat yield across global countries. The quadratic nonlinear response of global meat cattle

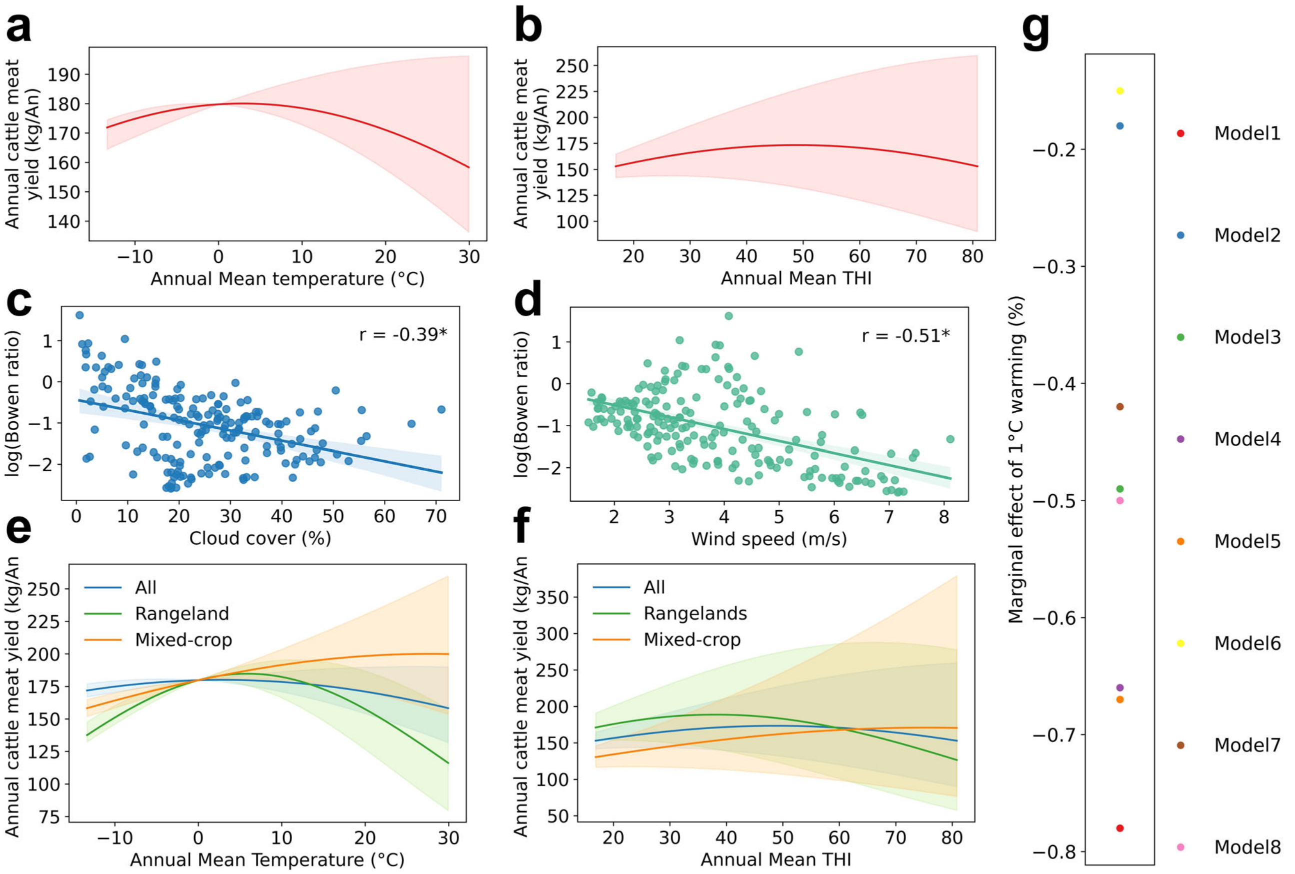

Fig. 1 Response of cattle meat yield to climate warming. The nonlinear response of cattle meat yield to annual mean temperature (**a**) and THI (temperature humidity index) (**b**), the shade areas represent the 95% confidence interval estimated by 1000 times of bootstrap. The dependency of the Bowen ratio (ratio of annual sensible and latent heat obtained from ERA5) is associated with annual average cloud cover (**c**) and wind speed (**d**) at the country scale, each dot represents one country, *r* is the correlation coefficient, with an asterisk denoting significance at 90%. The greater sensitivity of cattle meat yields to warming in rangeland than other livestock systems (**e**, **f**), the shade areas represent the 95% confidence interval estimated by 1000 times of bootstrap. The marginal effect of 1 °C warming on cattle meat yield is given by eight regression models (**g**), the model specifications of which refer to the Methods.

Table 1 The regression coefficients for the sensitivity of cattle meat yield to climatic and socioeconomic variables.

Variables (unit)	M1 (warm = T)	M2 (warm = THI)
Warm (°C for M1, NA for M2)	−0.0062***	0.009***
Warm^2 (°C^2 for M1, NA for M2)	−0.0002***	−0.0001***
Warm × Wind (°C × m s^{-1} for M1, NA × m s^{-1} for M2)	0.0013***	0.0005***
Warm × Cloud (°C × ratio for M1, NA × ratio for M2)	0.0001***	0.00006***
P (mm)	0.00002**	0.000007
GDPpc ($US)	0.000009***	0.000008***
CerYield (kg ha^{-1})	0.00002***	0.00002***
LPI (NA)	0.0015***	0.0013***
Adjusted R^2	0.33	0.34

[*] "Warm" represents the climate variables that can characterize warming. Temperature and THI are labeled as "Warm" in regression models M1 and M2, respectively. Wind and cloud represent the annual average wind speed and cloud cover. *P* annual total precipitation, *GDPpc* GDP per capita, *CerYield* cereal yield, *LPI* livestock production index. Stars represent the significant level: *<0.1, **<0.05, ***<0.01. The unit "NA" means non-dimensional variables, and the unit "ratio" represents a 0–1 ratio, 0 is 0%, and 1 is 100%.

yield to climate warming indicates the sensitivity of cattle meat yield to warming depends on the annual average temperature, such that the impact of warming on countries located in different latitudes is unequal.

The unequal impacts are found across major producing countries (Fig. 3a, b). The top 10 countries (measured by total cattle meat production in the year 2020) are located in diverse temperature zones, including temperate (e.g., China, the U.S., Russia, Turkey, and France), subtropical (e.g., Argentina, Australia, and Mexico), and tropical (e.g., Brazil and India). Temperature warming increases cattle meat yield in Russia (Fig. 3c), which is the northernmost among the top 10 cattle-producing countries, whereas the warming of annual average temperature reduces cattle meat yield in 7 of 10 countries (Fig. 3c). The countries with annual average temperatures closer to the optimal temperature threshold, like China and the U.S., undergo both increased cattle meat yield due to cold reduction and declined cattle meat yield caused by reinforced heat stress

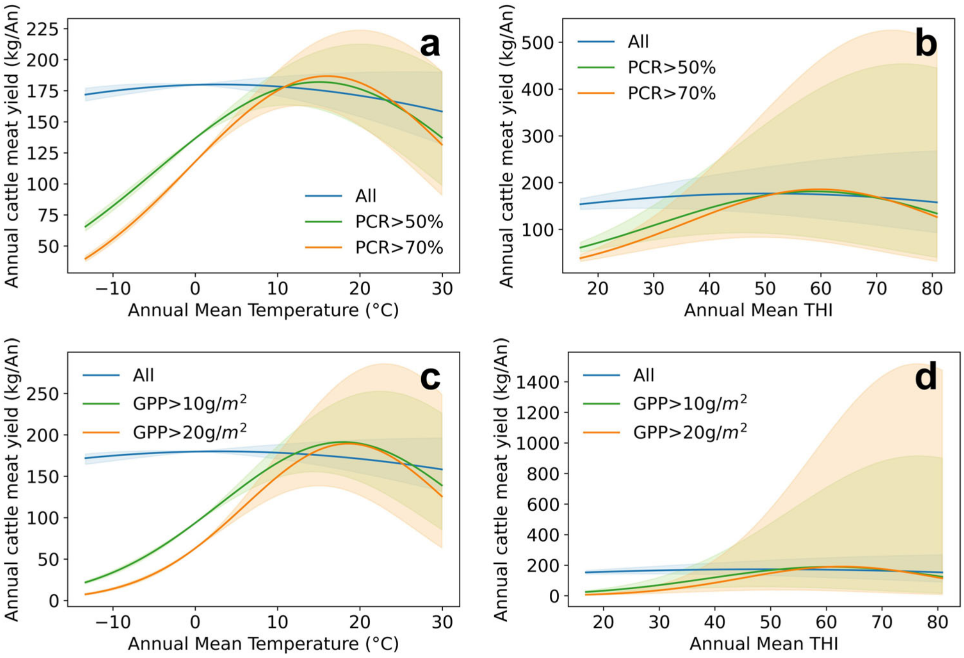

Fig. 2 Divergent response of cattle meat yield to climate warming. The divergent responses of cattle meat yield to annual mean temperature (**a**, **c**) and THI (**b**, **d**) across different pasture land fractions (quantified by PCR), pasture land productivity (quantified by GPP). THI temperature humidity index. PCR pasture and cropland ratio, which is quantified by the ratio of pasture area and overall area of pasture and cropland area. GPP multi-year average country-level gross primary production given by 14 land surface models. The shade areas represent the 95% confidence interval estimated by 1000 times of bootstrap.

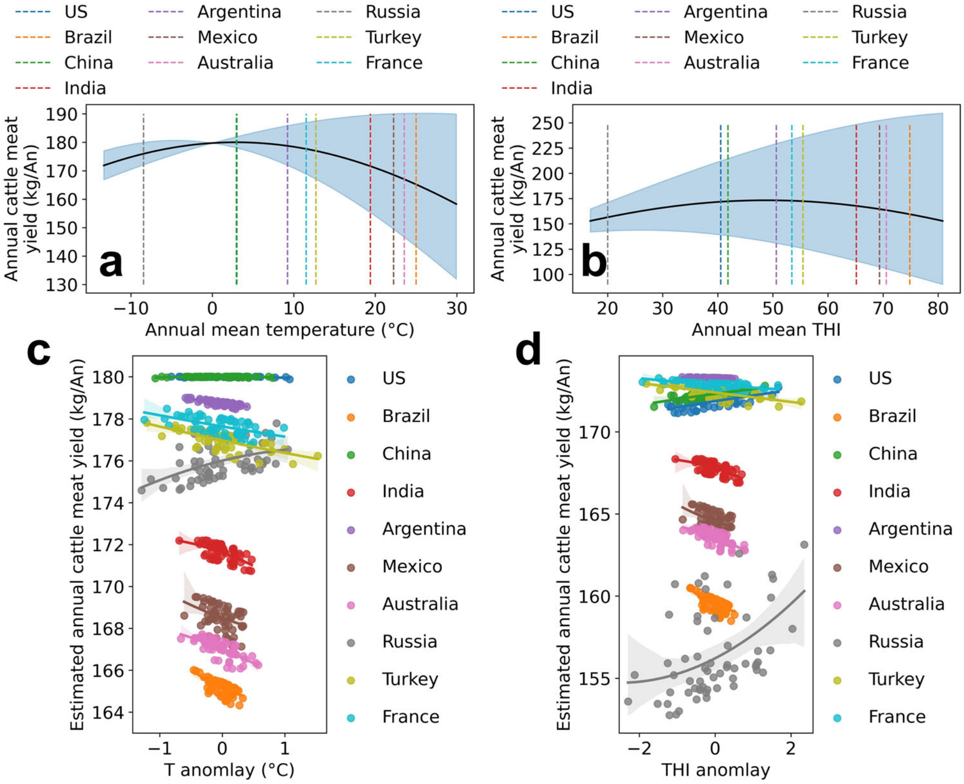

Fig. 3 The divergent response of cattle meat yield to climate warming across top 10 cattle meat producing countries. The response of annual cattle meat yield to warming quantified by annual mean temperature (**a**) and temperature humidity index (**b**) in the top 10 cattle-producing countries. The estimated annual cattle meat yield under T (**c**) and THI (**d**) anomaly given by regression models. T temperature, THI temperature humidity index. The T and THI anomalies are calculated with the annual T or THI deviation to the trend of T or THI. The shaded areas represent the 95% confidence interval estimated by 1000 times of bootstrap.

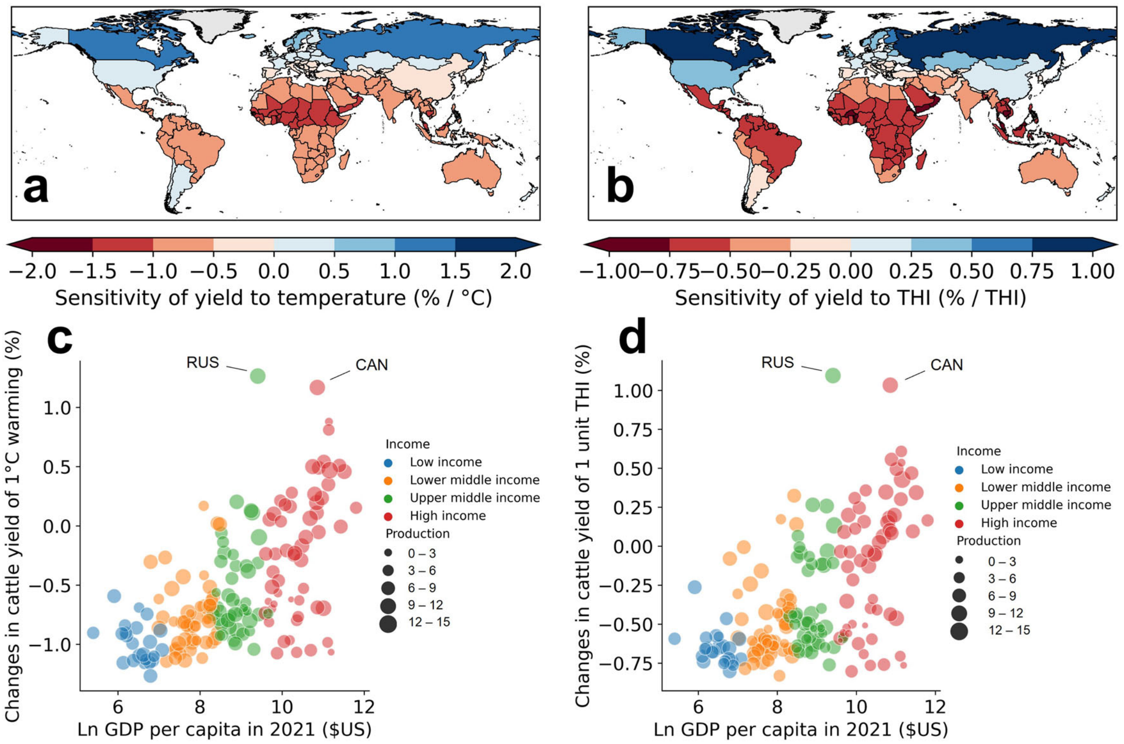

Fig. 4 The divergent sensitivity of cattle meat yield to climate warming. The spatial pattern of annual cattle meat yield response to annual mean temperature (**a**) and THI (**b**), THI temperature humidity index. The sensitivity of annual cattle meat yield to climate warming is correlated with economic development (GDP per capita) (**c**) and income levels (**d**), each dot refers to one country, RUS Russia, CAN Canada.

(Fig. 3c). For the regression using THI, only the cattle meat yields in the US, China, and Russia are positively correlated with THI anomaly (Fig. 3b, d).

Moreover, the unequal impacts of warming are found across countries with different income levels (defined by the World Bank) and economic production. Specifically, low-income countries are more vulnerable to the effects of warming. 1% yield loss on average is found under 1 °C warming, whereas the marginal effect of 1 °C warming on cattle meat yield in high-income countries is only −0.2% (Fig. 4a, c). The marginal effect of a 1 unit increase of THI on cattle meat yield in low-income countries is average −0.7%, and that in high-income countries is around zero (Fig. 4b, d). It is urgent for low- and middle-income countries to adopt new species that can face new thermal environments in the future[34] because they are located in hotter regions and will experience increasing demand for livestock products simultaneously[19].

The future climate warming aggravates the unequal impacts on cattle meat yield across global countries. The projected effect of warming on cattle meat yield exacerbates the unequal impacts of climate warming. Compared with the unequal impact in lower emission scenarios, those in higher emission scenarios have become greater (Fig. 5a, b). The largest yield loss difference is found in SSP3-7.0, the yield losses between low- and high-income countries have reached 3.2% (Fig. 5a, b). The spatial pattern of unequal burden is also clear. The countries located in low- and mid-latitudes are more likely to experience greater cattle meat yield loss than those in high latitudes, which is consistent in SSP1-2.6 and SSP3-7.0 (Fig. 5c–f). The spatial pattern of yield losses estimated by statistical regression is consistent with those given by the bioenergetic equations that the value of cattle production losses in tropical regions is significantly greater than those in temperate regions under future emission scenarios[7].

Discussion

In this study, we used the cattle meat yield response to warming to highlight that livestock production is associated with climate change. In contrast to the crop-based system that has garnered considerable attention in the past decades[35,36], the livestock system is increasingly acknowledged as an emerging concern within the realm of sustainable food systems[37].

From the view of macroeconomy, the previous global non-linear impact of temperature on economic production at the macro scale is mainly supported by some basic productive components of an economy[3], such as labor supply[38], labor productivity[39], and crop[40]. Our results provide new evidence from livestock meat yield to explain the non-linear response relationship.

In terms of underlying mechanisms of climate warming impact on livestock meat yield, climate warming reduces the cattle meat yield through direct impact on animal performance and indirect impact on feed intake (Fig. 6). The cattle meat yield loss by heat stress impacts on animal performance can be attributed to (1) suppressed immune and increased susceptibility to diseases that threats the health of cattle[9,41,42]; (2) reduced fertility caused by reduced ovarian function, reduced motility of spermatozoa, and inhibition of embryonic[43,44]; (3) reduced food intake and accelerated breath that jointly reduce the growth rate and energy can be used to protein accumulation[8,45,46]. Despite the direct impact of heat stress on animal performance, the cattle meat yield can also be harmed by the adverse effect of heat stress and concurrent drought on rangeland, which is likely to induce less eating and result in loss of weight. The dominant stresses on vegetation productivity over rangeland are (1) heat that reduces the rate of photosynthetic carbon sequestration[47] when temperature exceeds the optimal threshold[48]; and (2) drought that results in early senescence and less carbon uptake of rangeland productivity[49,50], sometimes increase the cattle water demand[10,51]. (3) compounding hot-dry

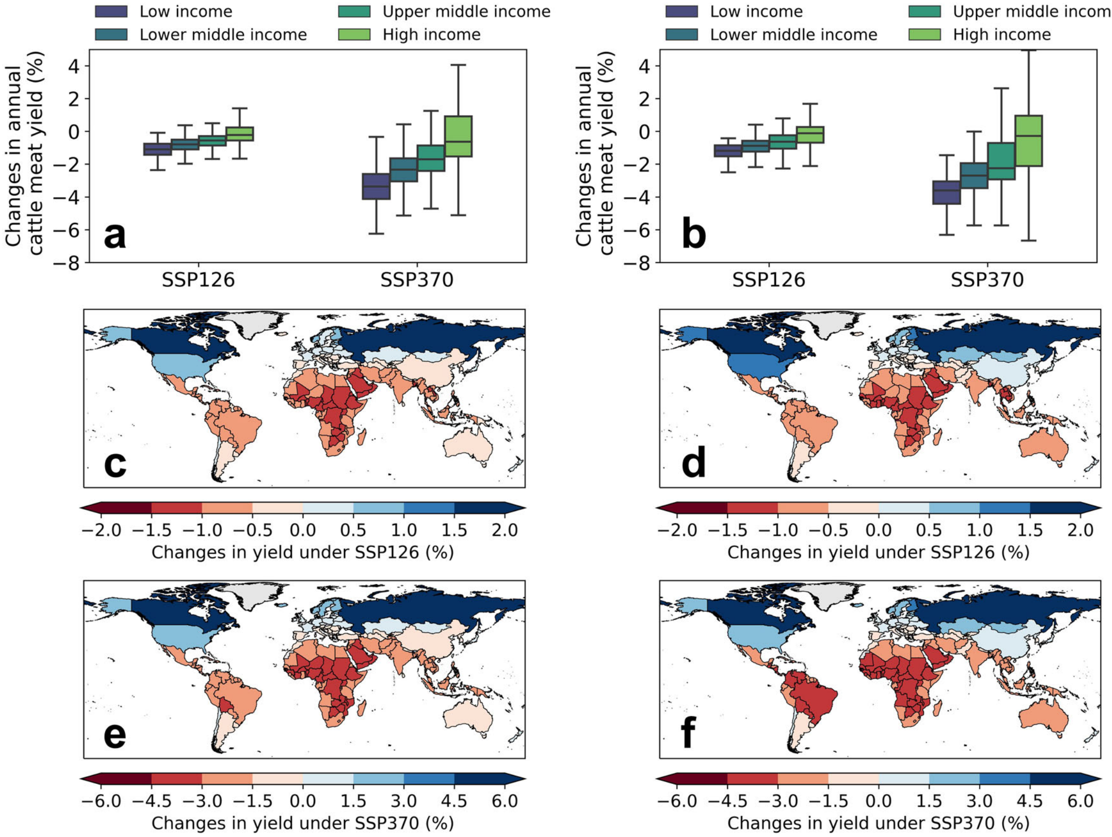

Fig. 5 Future projection of cattle meat yield under climate scenarios. The projected changes in annual cattle meat yield for 2081–2100 relative to 1990–2014 driven by regression model M1 with temperature specification (**a**, **c**, **e**) and regression model M2 with THI specification (**b**, **d**, **f**), respectively. The range of the boxes represents the uncertainty of five GCMs and differences across countries. The projection assumes no future technical progress. The center line of the box is median, the box limits are upper and lower quartiles, and the whiskers are 1.5× interquartile range.

aggravates the negative effect because rising temperature tends to co-occur with low soil moisture[52,53] and high VPD[54].

Compared with the increased annual cattle yield caused by technological development, the climate-driven effect on cattle meat yield is remarkably small. Without considering the management changes, climate warming will only result in a 3.7% reduction of the global average cattle meat yield in SSP370 at the end of this century. Although we cannot anticipate animal behavioral adaptation and management improvement in the future, current long-term increased trends of cattle meat yield at the country level can indicate the threats of climate warming to global cattle meat yield are within the capacities of livestock producers.

The unequal impacts of climate warming on cattle meat yield across countries are significant between tropical and temperate regions. The quadratic response curve of cattle meat yield to climate warming indicates the sensitivity of cattle meat yield depends on local temperature. From the perspective of mechanism, local temperature determines the climatological conditions of the ecosystem. Different climatological conditions will respond to warming divergently. Climate warming in hotter regions will be more likely to exacerbate the occurrence of heatwaves[55], which is detrimental to both animal performance and crop- or grass-based food intake. In colder regions, however, climate warming will melt the snowpack[56], which provides freshwater resources and warmer habitats for animals. Therefore, the unequal impacts of climate warming on cattle meat yield can be attributed to the divergent responses of ecosystems to warming. To alleviate the unequal impacts, adaptation strategies at local and global scales should be made. At the local scale, increasing irrigation for cropland-feed systems animal showers, adopting heat-tolerance domestic animal species, and preventing diseases can be conducted[34].

There are still some uncertainties and limitations to this study. The cattle meat yield we used can only represent the productivity of the livestock system at the individual level. Our empirical approach characterizes the impact of climate warming on cattle meat yield based on the current country-level data, such that some behavioral adaptation, like extensive grazing and redistributing grazing time within the country, are hard to capture. The historical response cannot be used to anticipate the potential tipping points for climate change impact on cattle meat yield. Additionally, in some developing countries the cattle meat yield is not continuous. The data unavailability is another source of uncertainty. Moreover, the climate shock in the integrated global livestock supply chains can also lead to ripple effects on livestock production. For instance, live animal transportation is influenced by transport network disruptions and infrastructure damage due to heat stress, which in turn contributes to poor animal performance or even death[57–59]. Besides, the negative effect of heat stress and diseases on labor availability and productivity restricts the efficiency of the livestock supply chain[10]. These ripple effects of climate warming on the livestock supply chain have not been quantified in this study, but the potential risk should be considered when developing adaptation strategies.

Methods

Country-level cattle meat yield and socioeconomic data. Cattle (beef and veal) meat yield (Meat with the bone, fresh or chilled) at

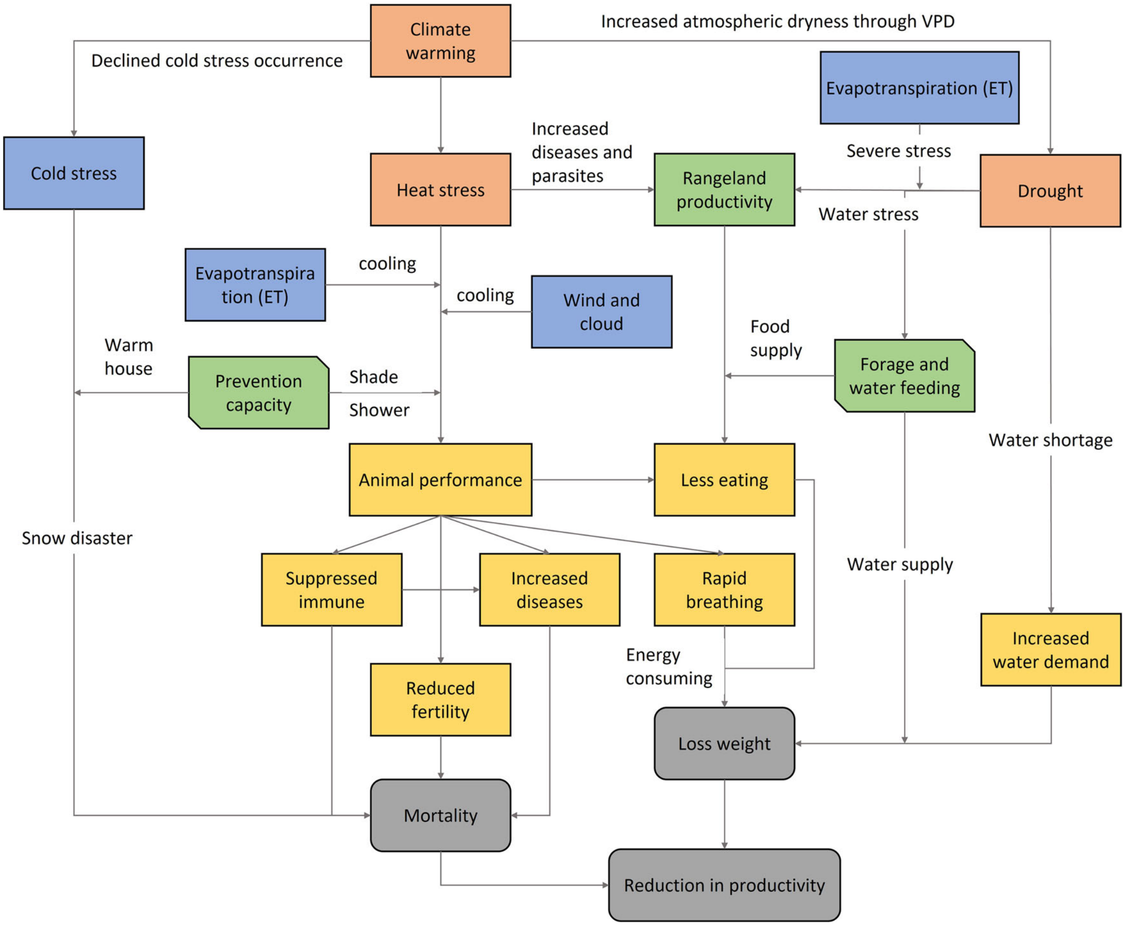

Fig. 6 The mechanism of climate change impacts on livestock productivity. The mechanism of climate change impacts on livestock productivity. Diagram of the main processes by which climate warming affects the cattle meat yield and livestock system.

country scale from 1961 to 2020 was obtained from the FAOSTAT database. The cattle meat yield is the ratio of total cattle meat weight and total number of cattle. Cattle meat yield only represents the productivity of the livestock system at the individual level. The country-specific GDP per capita, cereal yield, and livestock production index from 1961 to 2020 were obtained from the World Bank open data.

Climate data. We used three climate datasets from 1961 to 2020 to obtain the climate variables. The temperature and precipitation were obtained from the Climate Research Unit (CRU TS v4.06) with a monthly temporal scale and 0.5° spatial resolution. We selected CRU data to conduct statistical analysis because it is one of the most widely used interpolated data and possibly the best-available precipitation data at a global scale[30]. The wind speed was obtained from the Terra Climate, a monthly dataset with a 4 km spatial resolution[60]. The cloud cover was obtained from the ECMWF Reanalysis v5 (ERA5) with a monthly temporal scale and 0.25° spatial resolution. The cloud fraction given by ERA5 has been compared with the MODIS cloud fraction from 2002 to 2018[61], which indicates the ERA5 cloud fraction can capture the year-to-year variation of remotely sensed cloud cover (Supplementary Fig. 2). All climate variables are masked by the global distribution of cattle in 2010[62] and then aggregated to the country level. The future climate data were offered by five General Circulation Models (GCMs) obtained from Inter-Sectoral Impact Model Intercomparison (ISIMIP). These five GCMs (GFDL-ESM4, IPSL-CM6A-LR, MPI_ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL) are downscaled to 0.5° spatial resolution and bias-corrected under three emission scenarios, including SSP1-2.6, SSP3-7.0 and SSP5-8.5. As it is well documented that RCP8.5 was designed by CMIP as an unlikely outer-boundary case, we only selected SSP1-2.6 and SSP3-7.0. The five GCMs are good representatives of the CMIP6 ensemble that GFDL-ESM4, MPI-ESM1-2-HR, and MRI-ESM2-0 represent the low climate sensitivity and the IPSL-CM6A-LR and UKESM1-0-LL represent the high climate sensitivity[63,64].

Land use and gross primary productivity data. Pasture and cropland distribution were obtained from a global 10-km dataset provided by the EARTHSTAT. This dataset combines the inventory data and satellite-derived land cover products at a global scale[65]. The gross primary productivity (GPP) was obtained from the ensemble simulation of 14 land surface models that participated in MsTMIP. We used the SG3 outputs that were driven by the temporal variation of climate, land use, and atmospheric CO_2 concentration from 1961 to 2010[66].

Livestock system classification data. The 1-km gridded livestock system classification given by FAO has provided new evidence to split grassland-based livestock systems[5].

The framework of methodology. To quantify the impact of climate warming on global cattle meat yields, we address this question by the following steps: (1) we characterized the response of cattle meat yield to climate warming and used eight possible regression specifications to check the robustness of the response curve; (2) we explored the difference across livestock systems through separating grassland-based and cropland-feed livestock system and built regression models separately; (3) different sensitivity of cattle meat yield to climate warming for each country indicate the impact of climate warming on cattle meat yield is unequal; (4) under future climate warming, we detected the inequality of climate warming impacts on cattle meat yield.

Modeling climate effect on cattle meat yield. We conducted pooled panel regression models to estimate the effect of warming on cattle meat yield. As we focused on the response of annual cattle meat per animal to climate warming at the individual level, we used an equal weight for each country in the panel regression model. Regarding the divergent importance of cattle meat yield across countries depending on total meat production, we conducted a regression model weighted by country-level total meat production. Consistent responses of cattle meat yield to climate warming were found (Supplementary Tables 10 and 11). We used a quadratic term of temperature to measure the potential nonlinear effect of warming (regression model M1). The temperature and humidity index (THI) is introduced in an alternative regression model (regression model M2) to account for the effect of humidity. Considering the potential influences caused by different panel regression models, we used entity fixed-effects and time-entity fixed-effects panel regression models and found a similar response curve (Supplementary Fig. 3).

For both M1 and M2, the annual total precipitation, average wind speed, and cloud cover fraction were also included in the regression models. The linear function of annual total precipitation is used to represent the potential effect of drought on cattle performance[50] and food intake[67], which affects the viability of livestock production[68]. To account for the potential cooling effect of wind and cloud cover on heat stress[12], annual average wind speed, and cloud cover interact with annual mean temperature or THI.

Moreover, the cattle meat yield can be boosted by socioeconomic development, such as disaster prevention capacity (annual GDP per capita, GDPpc)[69], potential feed intake offered by cereal (annual average cereal yield, CerY)[70], capacity of transforming cattle meat yield to products (annual livestock production index, LPI). These factors jointly constitute the socioeconomic resilience of the livestock system[71].

The regression model M1 and regression model M2 are expressed as follows:

$$\begin{aligned}\log(Y_{i,t}) = {} & \alpha_1 t + \alpha_2 t^2 + \beta_0 + \beta_1 T_{i,t} + \beta_2 T_{i,t}^2 + \beta_3 T_{i,t} \times Wind_{i,t} \\ & + \beta_4 T_{i,t} \times Cloud_{i,t} + \beta_5 P_{i,t} + \beta_6 GDPpc_{i,t} \\ & + \beta_7 CerY_{i,t} + \beta_8 LPI_{i,t} + \varepsilon_{i,t}\end{aligned} \tag{1}$$

$$\begin{aligned}\log(Y_{i,t}) = {} & \alpha_1 t + \alpha_2 t^2 + \beta_0 + \beta_1 THI_{i,t} \\ & + \beta_2 THI_{i,t}^2 + \beta_3 THI_{i,t} \times Wind_{i,t} + \beta_4 THI_{i,t} \times Cloud_{i,t} \\ & + \beta_5 P_{i,t} + \beta_6 GDPpc_{i,t} + \beta_7 CerY_{i,t} + \beta_8 LPI_{i,t} + \varepsilon_{i,t}\end{aligned} \tag{2}$$

where the log(y) is the logarithm of annual cattle meat yield. $\alpha_1 t + \alpha_1 t^2$ is the quadratic time trend, which represents the unobserved technological progress, such as adopting new domestic animal species and better management practices (Supplementary Fig. 1). $T_{i,t}$ and $P_{i,t}$ are the annual mean temperature and total precipitation, respectively, for year t and country i. $Wind_{i,t}$ and $Cloud_{i,t}$ are the annual average wind speed and cloud cover fraction for country i and year t, respectively. The THI was calculated with the temperature (T, unit: °C) and relative humidity (RH, unit: %) (Thom 1959):

$$THI = 0.8 \times T + (RH/10) \times (T - 14.3) + 46.4 \tag{3}$$

Grassland-based livestock system splits. The sensitivity of grassland-based and cropland-feed livestock systems to climate warming and water consumption are different[72]. Considering the practice of grazing is associated with a fraction of pasture, pasture land productivity, and livestock system, we used three indices (pasture-cropland ratio, GPP, and livestock system classification) to split the grassland-based livestock system with other systems into subsets for separate regression.

We used the pasture-cropland ratio (PCR) to split the countries belonging to grassland-based systems (PCR > 50% and 70%). The pasture-cropland ratio was defined as the fraction of pasture on the sum of pasture and cropland:

$$PCR_i = \frac{Pasture_i}{Pasture_i + Cropland_i} \tag{4}$$

where the $Pasture_i$ and $Cropland_i$ are the areas of pasture and cropland in country i, respectively.

Also, we split the countries belonging to grassland-based livestock systems by using pasture land productivity (multi-year national average GPP > 10 g/m^2 and 20 g/m^2). The pasture land productivity aggregates the average gross primary production over pasture land at the country level to represent the difference in pasture land productivity across countries.

Additionally, we split the countries whose majority gridded class is grassland-based according to the FAO livestock system classification.

Robustness checks. We used other optional specifications of climate variables to test the robustness of the warming effect on cattle meat yield. Similarly, wind speed and cloud cover interaction with temperature or THI are also considered in the following alternative specifications.

Regression model M3. Regression model with a linear function of THI and frost day. The nonlinear response of cattle meat yield to temperature can be separated into heat and cold stress. To explicitly consider the heat and cold stress, we used the linear function of annual average THI and total frost day (FRS, obtained from the CRU dataset), and the interaction between THI and wind speed or cloud cover is considered in the regression model in the form of interaction terms (Supplementary Table 1):

$$\begin{aligned}\log(Y_{i,t}) = {} & \alpha_1 t + \alpha_2 t^2 + \beta_0 + \beta_1 THI_{i,t} + \beta_2 FRS_{i,t} + \beta_3 THI_{i,t} \\ & \times Wind_{i,t} + \beta_4 THI_{i,t} \times Cloud_{i,t} + \beta_5 P_{i,t} \\ & + \beta_6 GDPper_{i,t} + \beta_7 CerY_{i,t} + \beta_8 LPI_{i,t} + \varepsilon_{i,t}\end{aligned} \tag{5}$$

Regression model M4. Regression model with cumulative hourly THI over specific thresholds. Considering the heat stress occurs over a specific THI threshold, we used the cumulative THI over 72 (moderate) and 79 (high) to represent heat stress[16], and the interaction between THI and wind speed or cloud cover is considered into the regression model in the form of interaction terms:

$$\begin{aligned}\log(Y_{i,t}) = {} & \alpha_1 t + \alpha_2 t^2 + \beta_0 + \sum_{m=1}^{2} (\beta_1 THI_{i,t}^m \\ & + \beta_2 THI_{i,t}^m \times Wind_{i,t} + \beta_3 THI_{i,t}^m \times Cloud_{i,t}) + \beta_4 P_{i,t} \\ & + \beta_5 P_{i,t} + \beta_6 GDPper_{i,t} + \beta_7 CerY_{i,t} + \beta_8 LPI_{i,t} + \varepsilon_{i,t}\end{aligned} \tag{6}$$

where the four levels of cumulative hourly THI for country i and year t were used to quantify the different physiological heat stress.

$$THI^m = \sum_{h=1}^{H} THI_h, THI_h = \left\{ \begin{array}{l} m = 1 : 72 \leq THI_h < 79, otherwise, THI_h = 0 \\ m = 2 : 79 \leq THI_h, otherwise, THI_h = 0 \end{array} \right\} \tag{7}$$

where the THI^m ($m = 1$, 2) is the cumulative THI over different physiological thresholds. The THI_h is the hourly THI calculated with the ERA5-land dataset. The sensitivity of cattle yield given by the regression model M4 can refer to Table S2.

Regression model M5 and M6. Regression model (M1 and M2) with alternative wind speed datasets, i.e., ERA5. The sensitivity of cattle meat yield given by the regression models M5 and M6 can be referred to in Supplementary Tables 3 and 4.

Regression models M7 and M8. Regression model by considering the water withdrawal for livestock (watering and cleaning, obtained from FAO AQUASTAT). As the water shower can mitigate heat stress, we used an interaction term between temperature or THI and livestock water withdrawal. The sensitivity of cattle yield given by the regression model M7 and M8 can be referred to Supplementary Tables 5 and 6, respectively.

Future projection. We projected the future changes in cattle meat yield during 2081–2100 in SSP1-2.6 and SSP3-7.0 relative to the baseline (1985–2014) using the regression model M1 and M2 with five General Circulation Models (GCM) that participate in Coupled Model Intercomparison Project Phase 6 (CMIP6).

Data availability

Cattle meat yields are available from https://www.fao.org/faostat/en/#data. The country-specific GDP per capita, cereal yield, and livestock production index are available from (https://data.worldbank.org/?iframe=true). Climate Research Unit is available at https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.06/. The ERA5 data are available from (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). The pasture and cropland map are available from (http://www.earthstat.org/). The global land GPPs of MsTMIP are available from (https://nacp.ornl.gov/MsTMIP.shtml).

Code availability

The script used to run the regression model is available through zenodo at: https://doi.org/10.5281/zenodo.8420480.

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W.L.: conceptualization, methodology, data curation, formal analysis, writing—original draft, writing—review & editing. J.Z. and Y.M.: methodology, writing—review & editing. S.C. and Y.L.: writing—review & editing.

Competing interests

The authors declare no competing interests.

Additional information

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