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The Effect of Climate Change on Herbaceous Biomass and Implications for Global Cattle Production

Kate Vaiknoras, Greg Kiker, Ephraim Nkonya,
Savannah Morgan, Jayson Beckman,
Michael E. Johnson, and Maros Ivanic

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Abstract

Climate change may affect livestock production—particularly cattle—by changing the available herbaceous biomass (nonwoody plants such as grasses that are consumed by livestock) on rangelands. This report uses G-Range (a global, gridded rangeland model) to simulate the spatial and temporal effects of changes in temperature and rainfall as projected by a climate change scenario of high greenhouse gas concentration known as Representative Concentration Pathway 8.5. We find that, on average, global herbaceous biomass declines by 4 percent, with wide regional variation. Some regions experience increases in herbaceous biomass, particularly those with cooler climates where warmer temperatures may benefit plant growth, such as Northern Europe. Other regions may experience losses, such as West Africa, which more than offset gains elsewhere. This report also estimates how these changes may affect cattle production globally and by region. Rangeland beef and milk production could increase in some regions, particularly in North America, while falling in others, leading to negligible change on a global level for beef production and a 1-percent reduction in milk production. If herbaceous plants respond positively to higher levels of carbon dioxide in the atmosphere, losses to herbaceous biomass would be mitigated, leading to a 12-percent gain in beef production and an 11-percent gain in milk production.

Keywords: Climate change, cattle, meat production, milk production, rangelands, herbaceous biomass, simulation model, G-Range

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About the Authors

Kate Vaiknoras, Jayson Beckman, Michael E. Johnson, and Maros Ivanic are economists with the USDA, Economic Research Service (ERS), Markets and Trade Economics Division. Ephraim Nkonya is an economist with the USDA, ERS, Resource and Rural Economics Division. Greg Kiker is a professor in the Department of Agricultural and Biological Engineering at the University of Florida. Savannah Morgan is an environmental data science manager at the Dallas Fort Worth International Airport. She worked on this study as a graduate student at the University of Florida.

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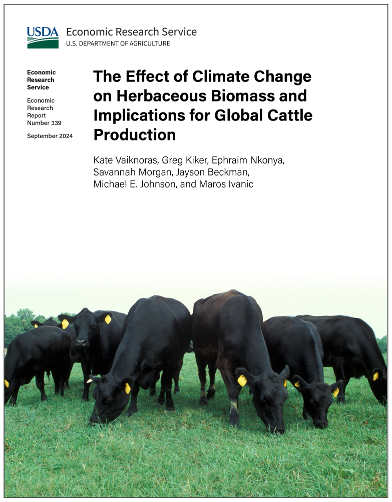

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What Is the Issue?

Climate change may affect plant growth, including grasses that cattle and other livestock feed on—ultimately affecting livestock production. This development has the potential to affect livestock producers and consumers of animal products around the world. This report used G-Range (a simulation model) to estimate changes in herbaceous biomass on rangelands by 2050 under a high-greenhouse gas concentration climate change scenario. Increased carbon dioxide (CO_2) concentrations promote growth in some plants by increasing the rate of photosynthesis, a process known as carbon fertilization. Because there is scientific uncertainty about how plant growth may respond in a sustained way to increased atmospheric carbon dioxide, this report simulated results that considered a positive carbon fertilization effect on plant growth in rangelands and results with no such effect. We then used productivity equations to estimate how these changes in herbaceous biomass could affect beef and milk production. Climate change may affect livestock production in other ways, such as causing heat stress for animals, reducing water availability, and promoting pathogens. Thus, this report does not capture all potential effects of climate change on livestock.

What Did the Study Find?

This study estimated a 4-percent decline in total global herbaceous biomass on rangelands by 2050 under a climate scenario of high greenhouse gas concentrations (Representative Concentration Pathway (RCP) 8.5) if there was no positive carbon fertilization effect. Results for the effect of climate on herbaceous biomass varied widely by region.

- This estimate represents a loss in food availability for cattle and dairy cows that rely on grasslands as forage.
- In Africa, every subregion experienced a loss in herbaceous biomass. Western Africa had the largest losses: Around 34 percent of its herbaceous biomass was lost without carbon fertilization. Several other regions would lose herbaceous biomass as well, such as South and Central America.

- Some regions, particularly those with cooler climates such as North America and Northern Europe, would gain herbaceous biomass as warming temperatures and/or changes in rainfall facilitated plant growth. Even within gaining regions, however, some areas would lose herbaceous biomass.

If herbaceous plants respond positively to increased atmospheric carbon dioxide, global losses would be more than offset. It was estimated that herbaceous biomass would increase by 7 percent under RCP 8.5.

- If carbon fertilization leads to increased plant growth, more regions would see gains in herbaceous biomass, including East Africa, Australia, and New Zealand.

This report also estimated changes in potential beef and milk production stemming from changes in herbaceous biomass availability in rangeland areas with at least one cow per grid square (55 kilometers by 55 kilometers). In general, regions that lost herbaceous biomass would lose meat and milk production, while regions that gained in biomass would gain in production. Some regions that gained herbaceous biomass, particularly North America, had widespread and highly productive beef and milk production: Gains in these regions offset losses in other regions. As a result, we estimated that globally, without carbon fertilization, potential beef production by cattle fed with rangeland herbaceous biomass would remain about the same, and milk production would fall by 1 percent. With carbon fertilization, potential beef and milk production would expand by 12 percent and 11 percent, respectively, as a result of increased biomass availability.

How Was the Study Conducted?

This report used a global, gridded ecosystem model called G-Range to simulate the effects of climate change scenarios on global mean herbaceous biomass. We focused our analysis on herbaceous (grass) biomass because this is the type of biomass that is grazed by cattle. The change in herbaceous biomass globally and regionally was estimated from 2017 to 2050. The simulations assumed a climate scenario under a relatively high level of future greenhouse gas concentrations called RCP 8.5; although, in the time frame examined, there was little variation among RCP scenarios. Seven different sets of climate data were used to account for uncertainty in future weather patterns under RCP 8.5; the results are an average of these seven. There was also uncertainty in how plants would respond to increased carbon dioxide in the atmosphere, so the results were estimated for different assumptions regarding plant responses under RCP 8.5.

To determine how climate change effects on herbaceous biomass affect beef and milk production, the herbaceous biomass results were entered into productivity equations that included regionally specific parameters representing the importance of herbaceous biomass in animal diets, meat and milk productivity, and more. The areas modeled were also restricted to those with cattle present, according to the most recently available data (2015). This study is the first to our knowledge to combine a formal productivity analysis with simulated herbaceous biomass changes, allowing us to translate changes in herbaceous biomass due to climate change into changes in beef and milk production. Thus, the total changes in beef and milk production on rangelands were calculated by region in 2050 and compared to 2017.

The Effect of Climate Change on Herbaceous Biomass and Implications for Global Cattle Production

Introduction

The Food and Agricultural Organization of the United Nations (FAO) (2023a) noted that livestock contributes about 40 percent of the global value of agricultural output in developed countries and 20 percent in developing countries. Livestock is an important part of the livelihoods of individuals and communities, employing 1.3 billion people worldwide and directly supporting 600 million smallholder farmers in developing countries (Thornton et al., 2006; Pandey & Upadhyay, 2022). Livestock animals (such as cattle) provide protein and calories for human diets and are a source of income, labor, transportation, and nutrients (through manure) for farmers. In many developing countries in Africa, Latin America, and Asia, livestock is considered a capital asset and a safety net for the poor (Herrero et al., 2013). Yet, these regions of the world are expected to be most affected by climate change (African Development Bank Group 2023).

Demand for animal products is expected to grow as human populations increase in urban areas and incomes rise, particularly in developing regions (Komarek et al., 2021). However, a changing climate could threaten livestock production in many ways. One way is by altering the quantity and quality of food available for animals as feed, as rising temperatures and changing rainfall patterns affect plant growth (Rojas-Downing et al., 2017). Much literature has focused on climate change effects on crop production (e.g., Hasegawa et al., 2022; Zhao et al., 2017), some of which is typically used as animal feed. Other literature has found that climate change may reduce the quantity of rangeland biomass available for livestock animals to graze on, with the worst agricultural outcomes predicted in some of the poorest regions of the world (Boone et al., 2018; Godde et al., 2020).

We used a gridded, monthly simulation model called G-Range to predict changes in rangeland herbaceous biomass by the year 2050 due to changes in projected climate data (specifically, monthly precipitation and maximum and minimum temperatures) under a high-greenhouse gas concentration climate scenario. This simulation was similar to previous studies, including Boone et al. (2018) and Godde et al. (2020), which also used G-Range to predict changes in biomass due to climate change. Our main contribution to the literature is to provide a formal analysis of how these changes in biomass may affect global and regional beef and milk production. To do this analysis, we adapted the production analysis framework used by Kwon et al. (2016), who estimated changes in beef and milk production due to biomass degradation from 2001 to 2011. Kwon et al. (2016) obtained a measure of biomass degradation using observed remotely-sensed data. While the remotely-sensed data allowed them to examine past biomass changes, it did not allow for forward-looking analyses. Our study combined the biomass simulation from G-Range with the formal production analysis of Kwon et al. (2016) to estimate how changes in biomass (due to climate change) may affect future beef and milk production. We presented results globally, regionally, by level of economic development, and by level of cattle concentration on the landscape, to highlight the distributional effects of climate change on livestock.

We focused our analysis on the rangeland cattle production of beef and milk. Cattle are a major type of livestock raised globally. Rangelands consist of grasslands and other landscape types that are (or can be) grazed by wild animals or livestock (including cattle). While not all cattle production takes place on rangelands, rangelands are a crucial landscape for cattle production and an important source of herbaceous biomass for foraging. Therefore, a limitation of our study is that it does not consider herbaceous biomass produced on other types of landscapes. We also did not examine all the ways that climate change may affect cattle production, such as increasing heat stress or the spread of pathogens (Thornton et al., 2022). Finally, we assumed production parameters such as conversion rates of feed to meat did not change over time (although we allowed them to vary regionally) and that there was no trade of herbaceous biomass between regions. While these assumptions may not be realistic, they allowed us to isolate the effects of biomass changes on production (absent any changes to production technologies, trade patterns, or climate change adaptation) by region.

Cattle Production on Rangelands

Cattle and other livestock can be produced in several types of production systems, which are largely defined by the type of feed dominant in the animals' diets. Mottet et al. (2017) estimated that globally, 46 percent of dry matter feed for livestock comes from grass and leaves (the remainder comes from crop residues and fodder crops, grain and oil seed cake, and other sources). Cattle produced on rangelands (the focus of our paper) are primarily grazed, with grass and leaves as the primary source of feed. By contrast, in mixed livestock systems that combine livestock and crop production, at least 10 percent of feed comes from crop byproducts, and in landless systems, less than 10 percent of feed is produced on-farm (Steinfeld & Mäki-Hokkonen, 1995). Grazing systems support ruminant species, including large cud-chewers such as cattle and buffalo, and small ruminants including goats and sheep. For more information on rangelands, see the box: What are Rangelands?

What Are Rangelands?

Rangelands are areas of grasses, other grass-like plants, shrubs, and sometimes trees that are grazed or can be grazed by wildlife animals and/or livestock. In contrast to shrubs and trees, grasses are considered herbaceous plants because grasses do not have woody stems and can be grazed by cattle. Types of rangelands include grasslands, savannas, deserts, some woodlands, and tundra. More than half of the Earth's land surface (54 percent) is covered in rangelands. Grasslands are dominated by grasses and make up 44 percent of global rangelands and 23 percent of global terrestrial surface (International Livestock Research Institute (ILRI) et al., 2021). A majority (78 percent) of rangelands are considered drylands, which includes arid, semi-arid, and dry semi-humid areas (ILRI et al., 2021). Drylands are particularly vulnerable to degradation and desertification, a process by which vegetation in once-fertile lands decreases or disappears; important factors influencing desertification include climate, fire, grazing, agriculture, and atmospheric carbon levels.

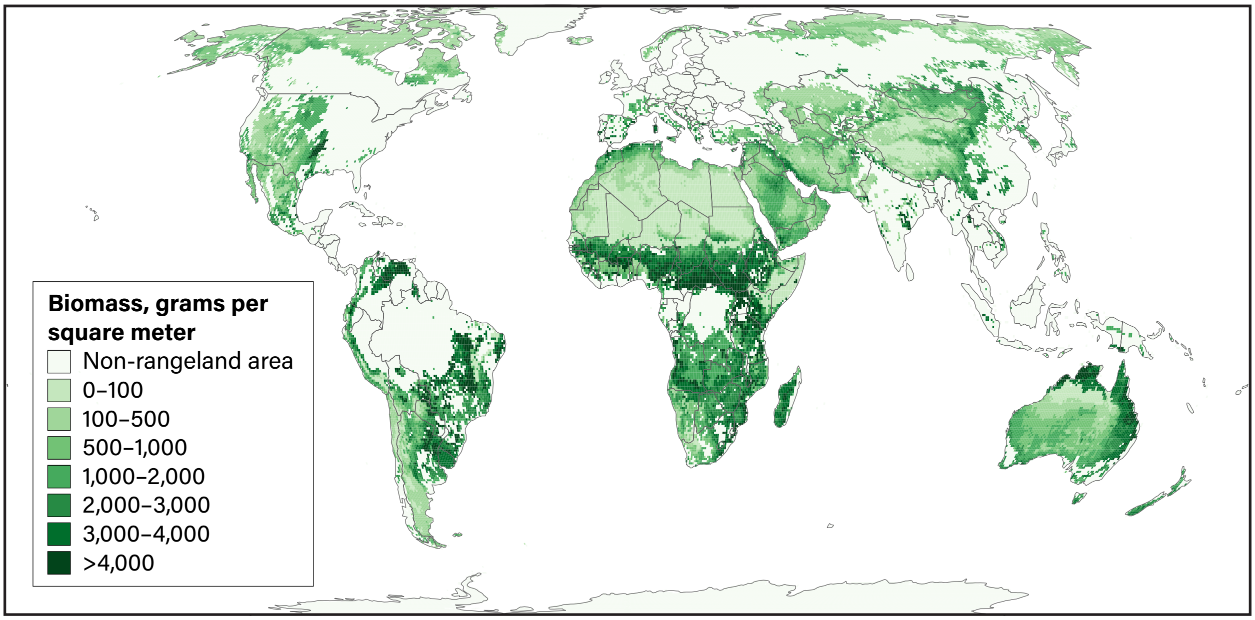
Livestock production is a dominant economic activity on rangelands, taking place on 84 percent of rangeland areas globally (ILRI et al., 2021). This finding is true on drylands specifically as well, where the most widespread land use is livestock production (United Nations Convention to Combat Desertification (UNCCD), 2017). Nearly half of livestock production on rangelands occurs in arid areas, which are mostly not suitable for crop production (ILRI et al., 2021). Different types of pastoralism (or animal herding) take place on rangeland production systems globally, including:

- nomadism, when pastoralists move in irregular patterns,
- transhumant pastoralism, when pastoralists move their animals in a regular back and forth pattern, and
- pastoral farming/ranching, when pastoralists and their livestock remain in one place.

Where Are Rangelands Located?

G-Range identifies rangelands based on land cover type. Rangelands are present on all continents, except Antarctica (figure 1). The African landscape is dominated by rangelands, particularly the Sahelian region (which stretches from western Africa to Sudan), and in eastern and southern Africa. Australia is also mostly rangelands, other than along the southeastern and southwestern coasts. South America has rangelands along the western coast and throughout the central and eastern parts, and a smaller portion of the north. In North America, rangelands cover much of the western half of the United States and Mexico, northern Canada, and Alaska. Rangelands are the primary landscape in Central Asia and cover much of Eastern Asia, except for the coastal regions. The western parts of South Asia and the Middle East are also mostly rangeland regions. Southeast Asia, Central America, and Europe are mainly covered in other landscape types and not major rangeland regions.

Figure 1
Global distribution of herbaceous biomass on rangelands, 2017



Note: Biomass refers to herbaceous biomass concentrations that are estimated using the G-Range simulation model. Areas in white are not rangelands and are not modeled by G-Range.

Source: USDA, Economic Research Service using the G-Range simulation model using climate data from the GFDL-CM3 general circulation model (Donner et al., 2011).

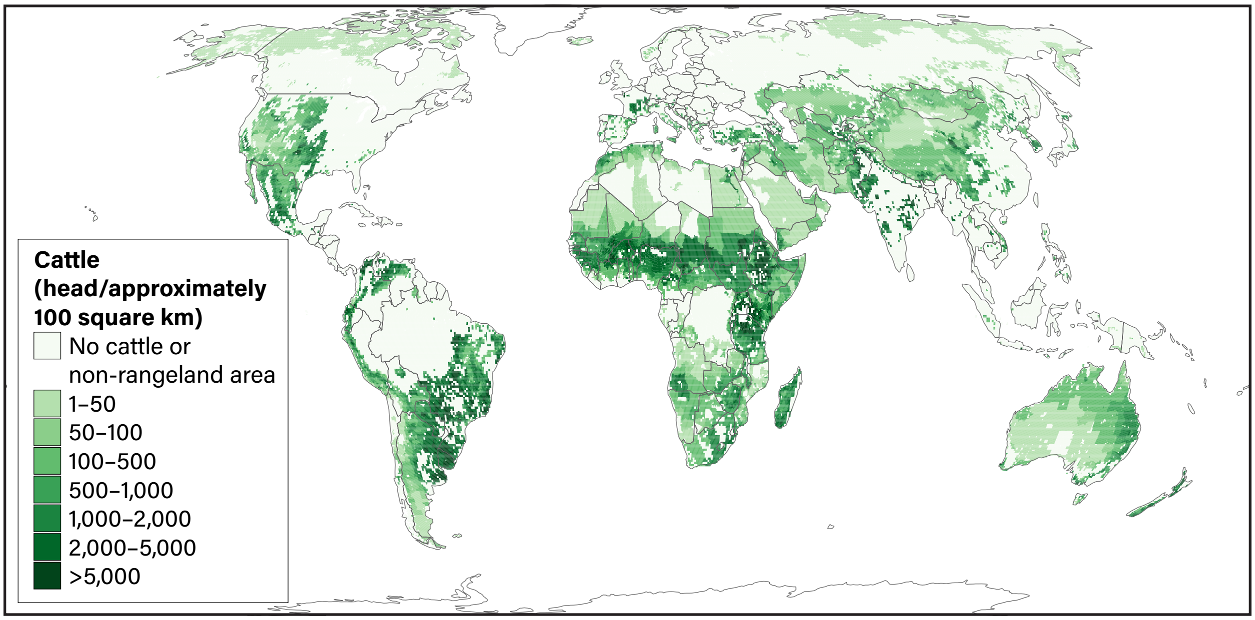
Rangelands contain different types of biomass, including herbaceous (or grass) biomass, shrub biomass, and tree biomass. While some grazing animals (such as goats) can consume different types of biomass, cattle only regularly consume herbaceous biomass. Rangeland areas with low amounts of herbaceous biomass include desert regions in Africa north of the Sahel, some parts of Australia, western South America, and Central Asia, as well as areas of high latitudes such as Canada. By contrast, areas that have large quantities of herbaceous biomass include the rangelands of Africa, eastern and northern South America, and the western and northern coasts of Australia.

Where Does Rangeland Cattle Production Take Place?

Our report focused on cattle beef and milk production because cattle are the dominant livestock species raised on rangelands globally. The areas of rangelands included in our meat and milk analyses are the areas that have cattle on them (figure 2). The areas of rangelands with the highest concentrations of cattle (including both beef and dairy cattle) are in the Sahelian region of Africa, parts of eastern and southern Africa, the Eurasian steppe, Eastern Australia, parts of South America, and the western half of North America. Other areas of concentration are scattered throughout other rangeland areas, although, in general, far northern latitudes and desert areas do not hold large concentrations of cattle.

Not all cattle production takes place on rangelands. For instance, cow-calf operations in the United States are located throughout the country, not only in defined rangelands. In addition, although milk is produced in all 50 States, more than 50 percent of dairy is produced in 5 States: California, Wisconsin, Idaho, Texas, and New York (USDA, ERS, 2023), some of which are dominated by rangelands while some are not (figure 2). Also, even cattle that are located on rangelands could be housed in barns and fed a mixture of feeds.

Figure 2
Global distribution of cattle on rangelands, 2015



km = kilometer.

Source: USDA, Economic Research Service using livestock distributions from the Gridded Livestock of the World dataset 2015 and area delineations of rangelands from the simulation model G-Range.

Cattle and other livestock production play a major role in local economies in many regions with high concentrations of rangeland cattle production. For instance, in Sub-Saharan Africa, livestock accounts for about 40 percent of total agricultural gross domestic product, and one-third of the global livestock population is located there (African Union Inter-African Bureau for Animal Resources (AU-IBAR), 2016; Panel, 2020). In the United States, a third of all farm operations had at least one beef cow in 2017 (Gillespie et al., 2023), while in New Zealand, more than 40 percent of national export income comes from pasture-fed animals (Moot & Davison, 2021). In South America, cattle inventories have grown in recent decades, particularly beef cattle (19 percent growth from 2000 to 2017), and several countries have large cattle production sectors: The highest production is in Brazil, followed by Argentina (Williams & Anderson, 2019). Therefore, shifts in herbaceous biomass and cattle production can have large consequences on livelihoods and economies.

Production systems vary by region. In some areas (such as Sub-Saharan Africa), production of beef and milk is dominated by small-scale production on rangelands. For instance, in Ethiopia, more than 70 percent of the population keeps cattle as a source of food, income, insurance, and social capital (UN Food and Agriculture Organization (FAO), 2018). Other, more developed regions still rely on rangeland grazing for a part of their cattle production. In the United States, beef production begins on cow-calf operations, where cows primarily forage on grasslands while raising their calves (ERS, 2022). After weaning, the calves may remain on the cow-calf operation for breeding or move through the production chain and generally end up in a feedlot. Brazil, Australia, and Mexico follow similar production systems (Millen et al., 2011; Greenwood et al., 2018; Peel et al., 2010).

How Climate Change May Affect Livestock Production

While this study mainly estimated the effects on cattle and other livestock through changes in herbaceous biomass, there are many ways that a changing climate may affect livestock.

Heat Stress

Animals have a range of temperatures under which they can function; when temperatures exceed this range, the animals can suffer heat stress. For instance, temperatures above 35 °C (95 °F) can activate stress responses in lactating dairy cows (Soumya et al., 2022). Heat stress depends on the level of humidity and on the genetics, life stage, and nutritional status of the animal (Rojas-Downing et al., 2017). Some of the ways animals respond to heat stress are increased water intake, reduced feed intake, and impaired reproduction that can limit fertility rates (Thornton et al., 2022). In the long-term, high temperatures may cause several health problems in cattle (Rojas-Downing et al., 2017). Some breeds of cattle are more sensitive to heat than others; for instance, high-producing dairy cattle and beef cattle with heavy weights and thick coats are particularly vulnerable to heat stress (Rojas-Downing et al., 2017).

Studies have shown that livestock in East Africa and West Africa experienced more severe heat stress over the past few decades than before, and the studies predict that worsening heat stress in the future may threaten meat and milk production in these regions (Rihimi et al., 2020; Rihimi et al., 2021). Thornton et al. (2022) found that heat stress was already constraining feed intake by 2005 in some parts of the world, such as Africa and South America. They estimated that by 2045, under a high-greenhouse gas concentration climate scenario, heat stress would likely cause a decline in beef production by 7 percent and a decline in milk production by 2 percent. They found that results varied by region, with the worst regional losses expected in Sub-Saharan Africa. Portions of Central America and South America, as well as Southeast Asia, were also expected to fare poorly. By contrast, cooler climates such as in North America and Europe would likely suffer fewer losses. Areas of high latitude, even within Africa such as the highlands of Ethiopia, were expected to suffer less.

Pathogens

Climate change could potentially speed the growth and spread of parasites and pathogens (Rojas-Downing et al., 2017; FAO, 2017). For diseases that are spread through vector-borne pests, water, or soil, or are associated with temperature and humidity—climate change can directly affect transmission. For example, Rift Valley fever is associated in East Africa with extreme weather events that may occur more frequently due to climate change, while West Nile Virus and others are exacerbated by higher temperatures (FAO, 2017). Climate change can also indirectly affect disease transmission if extreme weather events increase host-to-host contact by driving animal populations closer together (FAO, 2017).

Availability of Water

Climate change will likely affect availability and distribution of water by shifting precipitation patterns, causing more extreme droughts and heavy rainfall events and accelerating the melting of glaciers (United Nations Educational, Scientific, and Cultural Organization (UNESCO), 2020). It was estimated that the livestock sector uses about 8 percent of global freshwater supply (Schlink et al., 2010). Water is required to produce grass and feed, for animals to drink, and for processing. For instance, a dairy cow may require as much as 155 liters (40.9 gallons) of drinking water per day, depending on the size and milk productivity of the cow (Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA), 2015; FAO, 2019). Animal health will suffer without sufficient available water. However, increased temperature due to climate change may increase the livestock sector's water needs substantially. In addition, the risk of salination may affect livestock, as this risk can increase chemical and biological contaminants in waterways (Rojas-Downing et al, 2017; Nardone et al., 2010).

Quantity and Quality of Feed

Climate change can also affect cattle indirectly by affecting the foods that the cattle eat. Climate change can change the quantity and quality of available grazing biomass through increases in temperature, changes in precipitation patterns that can lead to water stress or flood and increases in atmospheric carbon dioxide (CO_2) levels.

Previous research has used simulation modeling to quantify the effect of climate change on rangeland biomass in the future due to climate change. Boone et al. (2018) used G-Range to model how climate change would affect net primary production and herbaceous net primary production. Net primary production is the rate or amount of biomass produced by a plant in an ecosystem over time. The authors estimated that (under a severe greenhouse gas concentration scenario) total net primary production would decline globally by 29 grams of carbon per square meter ($g\ C\ m^{-2}$) per year without carbon fertilization and 10 grams with carbon fertilization up until 2050 (the baseline is 2000). At the same time, herbaceous net primary production would decrease by 5 $C\ m^{-2}$ per year without carbon fertilization and increase by 3 $g\ C\ m^{-2}$ per year with carbon fertilization. They also estimated results under a moderate concentration scenario and obtained very similar results compared to the severe scenario (for herbaceous net primary production: a decrease of 5 or increase of 1 $g\ C\ m^{-2}$ per year for scenarios without and with carbon fertilization, respectively). They estimated large regional differences, with gains in northern regions such as the United States and Canada and large declines in Western Africa and Australia. Based on losses in forage availability and the placement of livestock globally, they estimated that livestock would decline 7.5 to 9.6 percent globally under the severe concentration scenario, which is equivalent to a global economic loss of $9.7 to $12.6 billion.

Godde et al. (2020) used the G-Range model to project changes in mean herbaceous biomass and variations in herbaceous biomass across months and years between 2000 and 2050 under mild and severe concentration scenarios, with and without carbon fertilization effects. They found that mean herbaceous biomass was estimated to decrease globally by 4.7 percent and that variation in herbaceous biomass both across months and years would likely increase. They estimated that many regions that now have low levels of livestock productivity and economic development (as well as high projected increases in human population densities) would likely experience large amounts of biomass loss for livestock production.

Other research used different simulation models to estimate changes in biomass due to climate change. Reeves et al. (2014) modeled effects of climate change on net primary productivity on U.S. rangelands to 2100. They found that rangeland net primary productivity increased by 0.26 percent per year after 2030, with significant regional variation. The Desert Southwest and Southwest were predicted to have the greatest declines. Weindl et al. (2015) used a simulation model to estimate changes in grass and crop yields from 2005 to 2045 globally due to climate change. They found that with no carbon fertilization effect, grass yields declined by 2 percent globally and agricultural production costs increased by 3 percent. With carbon fertilization, global grass yields increased by 14 percent.

While some of these studies conducted analyses to translate changes in biomass into changes in meat production, their production analyses were somewhat limited in scope. For instance, Boone et al. (2018) used parameters of livestock maintenance requirements and a global average of percentage dressed weight to calculate changes in global livestock, supported by herbaceous biomass and the economic cost of this loss. The authors did not provide estimates of livestock production changes by region.

Kwon et al. (2016) used previous changes in herbaceous biomass (between 2001 and 2011) to estimate losses in production, using a more indepth production analysis that is explained in the next section of this paper. Grassland declines have occurred and can be costly. They identified grassland degradation hotspots during that period using a Normalized Difference Vegetation Index (NDVI), a remotely sensed measure of vegetation greenness. They estimated changes in livestock production based primarily on loss of grassland biomass; the amount of meat and milk that could have been produced from this lost biomass; and the price of meat and milk. They estimated that the global cost of beef and milk production lost to grassland degradation from 2001 to 2011 was $6.8 billion in 2007 dollars (Kwon et al., 2016).

Methodology

The G-Range Model

We used the G-Range rangeland biomass simulation model to simulate the effects of climate change scenarios on mean herbaceous biomass. We then estimated the consequence of the changing quantity of herbaceous biomass on meat and milk production. Projected climate data, specifically average monthly precipitation and maximum and minimum monthly temperatures, were inputs into G-Range to simulate changes under climate change in the future for each grid cell. Data on soil properties from the Harmonized World Soil Database (Food and Agriculture Organization of the United Nations (FAO), International Institute for Applied Systems Analysis (IIASA), ISRIC-World Soil Information, Institute of Soil Science—Chinese Academy of Sciences (ISSCAS), and Joint Research Centre of the European Commission (JRC), 2012), and the proportion cover of herbaceous, shrub, and deciduous and evergreen trees were included (DeFries et al., 2000; Loveland et al., 2000). Nutrient cycling, water dynamics, soil carbon levels, plant growth, plant death, and grazing were simulated for each grid cell by month based on the characteristics of the grid cell and the changing temperature and precipitation data. Herbaceous biomass concentrations, which were an output of the G-Range model, were compared between different years to assess the effects of climate change on the availability of grassland forage for cattle. Boone et al. (2018) provided a thorough explanation of the G-Range model and its parameters, as well as how model parameters were validated such that the models are consistent with other model results and real-world conditions.

Simulation Scenarios

We simulated G-Range between 2017, our base year, and 2050. The simulations required assumptions of future greenhouse gas concentrations, how these concentrations would affect the climate, and how plants would respond. Future concentrations could be captured by four different representative carbon pathways

(RCPs)[1], where a higher number indicates greater concentrations. For context, by midcentury, RCP 2.6 projects a mean temperature increase of 1 degree Celsius (with a likely range of 0.4 to 1.6 degrees), while RCP 8.5 predicts a 2-degree Celsius increase (with a 1.4- to 2.6-degree range). After midcentury, the divergence between RCP predictions is greater (Intergovernmental Panel on Climate Change (IPCC), 2013). Previous literature using G-Range evaluated results under different RCPs and found little variation in the results (Boone et al., 2018). Therefore, we only used one scenario.

General circulation models (GCMs) are climate models used in weather forecasting that simulate the response of Earth's global climate system to increasing greenhouse gas concentrations. This analysis averaged results from seven different general circulation models, as done in previous work using G-Range (Boone et al., 2018).[2] These models provide climate data on monthly precipitation, maximum temperature, and minimum temperature that were used as inputs into the G-Range model. Thus, G-Range simulates changes in biomass due to shifts in temperature and precipitation, including rainfall and simulated changes to snow melt. Biomass may be affected by climate change in other ways, such as shifting wildfire patterns and deviations from average rainfall (such as instances of drought), but these other ways were not captured in our analysis. Furthermore, temperature and precipitation may have direct effects on animal health and well-being that are not captured by G-Range. G-Range is strictly modeling the changes in herbaceous biomass, which can indirectly affect livestock production. While our main results averaged the model results together, we also presented the results separately in the appendix to examine sensitivity of results to the choice of general circulation models.

Finally, we ran each model in two ways regarding carbon fertilization of plants: One holding carbon dioxide levels constant so that there was no fertilization effect and a second where plants responded positively to increased atmospheric carbon by increasing productivity. This is consistent with previous work using G-Range (Boone et al., 2018; Godde et al., 2020). G-Range incorporates carbon fertilization by introducing a multiplier on plant production based on projected atmospheric carbon for RCP 8.5 from Intergovernmental Panel on Climate Change projections (Meinshausen et al., 2011; Boone et al., 2018). The multiplier is the same across all biomes and does not account for varying distributions of C3 and C4 plants (see box, "Plant Responses to Increased Carbon in the Atmosphere").

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[1] These are RCP 2.6, RPC 4.5, RCP 6.0, and RCP 8.5.

[2] Following Boone et al. (2018), we use seven general circulation models. The models are BCC-CMS 1.1 (Wu, 2012); CSIRO-Mk3.6.0 (Collier et al., 2011); GFDL-CM3 (Donner et al., 2011); GISS-E2-R (Schmidt et al., 2006); HadGEM2.ES (Collins et al., 2011); IPSL-CM5A-LR (Dufresne et al., 2013); and MIR-CGCM3 (Yukimoto et al., 2012).

Plant Responses to Increased Carbon in the Atmosphere

How climate change affects agriculture depends partly on how plants will respond to increased concentrations of carbon dioxide in the atmosphere. Different plants may respond differently, depending on how the plants perform photosynthesis (the process that plants use to turn sunlight into energy). Plants use one of two types of photosynthesis, which differ in how they fixate carbon from the atmosphere: C3 photosynthesis (which most plant species use including wheat, rice, soybeans, and temperate grasses) and C4[1] photosynthesis (which evolved to help plants such as maize, sorghum, sugarcane, and tropical grasses reduce water loss in hot, dry environments). Generally, C3 plants are more prevalent in areas of lower temperature and/or early in the growing season, while C4 plants are found more in warm-weather climates. However, both types can be found within the same geographic areas. Increased carbon dioxide (CO_2) concentrations promote growth in some plants by increasing the rate of photosynthesis, particularly those that use C3 photosynthesis. This process is known as the carbon fertilization effect. However, there is uncertainty whether this process leads to sustained growth because the process is complicated and may be limited or short-lived (Cho, 2022). For instance, warming temperatures can also affect the amount of nitrogen available to plants and increase water needs, both of which may limit the carbon fertilization effect. Elevated carbon dioxide levels may reduce protein and nutrient concentrations in some plants (Cho, 2022).

If carbon fertilization occurs, it may mitigate some of negative effects of climate change on plant growth and agricultural productivity. To account for this potential effect but also the uncertainty regarding the process, many studies that have estimated the consequences of climate change on crops performed simulations with and without carbon fertilization (Hasegawa et al., 2022).

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[1] C3 photosynthesis uses the Calvin cycle for fixing carbon dioxide inside the chloroplast in mesophyll cells, while in C4 plants, photosynthesis is partitioned between mesophyll and bundle sheath cells (Wang et al., 2012).

Estimating the Effect of Grassland Biomass Changes on Cattle Production

The G-Range model provides simulation results of biomass changes for all rangeland areas on Earth. We then used these results to estimate changes to global and regional rangeland beef and milk production from 2017 to 2050 based on changes in herbaceous biomass on rangeland areas where cattle are present. We did this using a methodology from Kwon et al. (2016). The overall objective of this analysis was to determine changes in the quantity of grass dry matter consumed by cattle in a specific area and to then estimate the changes in resulting beef and milk production in that area.

We first calculated the average change in dry matter available for animals in each rangeland grid square based on the G-Range simulation results from 2017 and 2050. This calculation is in contrast to Kwon et al. (2016), who obtained their dry matter estimates from remotely sensed Normalized Difference Vegetation Index (NDVI) data. From this result, the estimated quantity of dry matter intake from grass biomass, or the amount of food consumed by animals, was calculated. Mathematically, dry matter intake (*DMI*) was calculated as (adapted from Kwon et al., 2016):

$$DMI_{ti} = biom_{ti}\gamma_i\kappa \qquad [1]$$

Here, dry matter intake was measured in metric tons in year *t,* in area *i*, equal to the area of a grid square (pixel) in the G-Range model. The quantity of standing herbaceous biomass that was available for animal foraging on average was captured by $biom_{ti}$. This measure comes directly from G-Range results and was averaged over the 12 months of each calendar year *t.* To calculate dry matter intake$_i$ $biom_{ti}$ is multiplied by two factors: κ and γ_i. γ_i is the contribution of grass to total feed intake; values came from Kwon et al. (2016) and were based on research from Bouwman et al. (2005). Values of γ_i of were calculated using weighted averages of the contribution of grass to total feed intake across different types of production systems by region. Because our analysis solely examined rangeland areas, where grazing was likely more common than in other areas, these results may be underestimates of the contribution of grass to total feed intake for our purposes. However, different types of production could take place on rangelands and these estimates accounted for that factor. For beef production, γ_i ranged from a low of 0.42 in the Near East, North Africa, and South Asia to a high of 0.85 in Sub-Saharan Africa. Values were lower for milk, ranging from 0.18 in the Near East, North Africa, and South Asia to a high of 0.75 in Sub-Saharan Africa. North America had midrange values for both: 0.65 for beef production and 0.43 for milk. κ was the share of above ground grass biomass consumed by livestock, which was assumed to be 0.33 both here and in Kwon et al. (2016).

Our approach next considered how meat and milk production P will respond to the changes in dry matter intake over our projection period (from 2017 to 2050). The change in dry matter intake was multiplied by several factors that reflected the variability in cattle production in terms of where cattle were located, productivity, and marketing, as follows (adapted from Kwon et al., 2016):

$$\mathrm{P} = \sum_{i=1}^{I} [DMI_{it=2050} - DMI_{it=2017}] x_i \tau_i \left(\frac{1}{\theta_i}\right) \qquad [2]$$

For changes in meat production, θ_i was the conversion factor of grass dry matter intake to the fresh weight of meat, which measures how much biomass an animal must consume to put on 1 kilogram of meat (Wirsenius et al., 2010). This parameter varied based on the region; regions with less efficient animals on average would have a higher conversion factor. For instance, according to Wirsenius et al. (2010), in Sub-Saharan Africa, it requires about 100 kilograms (220 pounds) of dry matter intake to produce 1 kilogram (2.2 pounds) of beef, but in North America and Oceania (Australia and New Zealand), it requires only 25 kilograms (55 pounds) of dry matter intake. Our analysis assumed that conversion rates, and therefore animal productivity, remained constant between 2017 and 2050. While this assumption may not be realistic, the assumption allowed us to isolate the effect on production that climate change has through its effect on herbaceous biomass.

The off-take rate was designated by the variable τ_i, which equals the number of animals disposed of from a farm (e.g., marketed or slaughtered) as a percentage of the average of initial and ending stock of animals kept (Negassa & Jabbar, 2008).[3] The off-take rate varied from 0.06 in South Asia to 0.25 in the United States and Canada. This analysis ignored any weight loss by animals that were not disposed of.

Finally, x_i indicates whether cattle were present on the grid square. For our main results, x_i was set equal to 1 if there was at least one cow on grid square i, and 0 otherwise. We, therefore, assumed that all herbaceous biomass that was used for meat and milk production was grown in areas where there were cattle; none was shipped from other areas where there were no cattle. We performed additional analyses where we set $x_i = 1$ if there were at least 10, 100, or 500 cattle on the grid square to assess how production shifts differ in areas of greater cattle concentration. Note that the number of cattle in a grid square did not enter production calculations; instead, the level of cattle density informs which pixels "count" in the aggregation of herbaceous biomass. Therefore, the production quantities we estimated represented potential production stemming from this herbaceous biomass. Information on where cattle were located came from the Gridded Livestock of the World (GLW) dataset (Gilbert et al., 2022), which is a spatial dataset on global cattle livestock distributions in 2015. Cattle distributions were thus held constant at 2015 levels. Because the GLW dataset has a different resolution than the G-Range model uses, we resampled the dataset to provide the sum of cattle on a G-Range pixel of 0.5 degrees.

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[3] $\tau_i = \frac{disposal}{0.5 * (S_1+S_2)} * 100$, where disposal= animals disposed of from a farm, S_1 = initial stock, S_2 = ending stock (Negassa & Jabbar, 2008).

For calculating changes in milk production, equation 2 remains the same except that θ_i was the rate of conversion from dry matter intake to fresh milk, which ranges from about 1 in North America and Western Europe to 7 in Sub-Saharan Africa. This conversion rate includes feed eaten both by milk cows and replacement heifers (Wirsenius et al., 2010). Therefore, not all feed was being immediately transformed into milk, increasing the estimate of total quantity being used in milk production. Here τ_i, was not included because milk production does not require that the animals be slaughtered. Finally, the production estimate for milk was further multiplied by the share of dairy cows at a national level obtained from FAO (Food and Agriculture Organization Corporate Statistical Database (FAOSTAT), 2023b), which ranged from about 0.1 to 0.5 to reflect the share of biomass going into milk production. Meat production was not modified by this factor, as it was assumed that both dairy cows and nondairy cattle can and will eventually be processed for meat.

After herbaceous biomass, meat, and milk production were calculated per grid square, we aggregated them by region. Our changes in regional beef and milk production estimates can be interpreted as the region's change (from 2017 to 2050) in total potential beef and milk production that comes from its cattle's consumption of herbaceous biomass that is produced on rangelands (where cattle reside) within that region. The estimates are most relevant for rangeland production areas themselves, although trade of herbaceous biomass within each region was implicitly allowed: Herbaceous biomass produced in rangeland grid squares could theoretically be transported to feed cattle located anywhere in the region. However, we assumed there was no trade of herbaceous biomass across regions and that each region in our analysis produced meat and milk using only the herbaceous biomass the region produced.

Results

Herbaceous Biomass Results

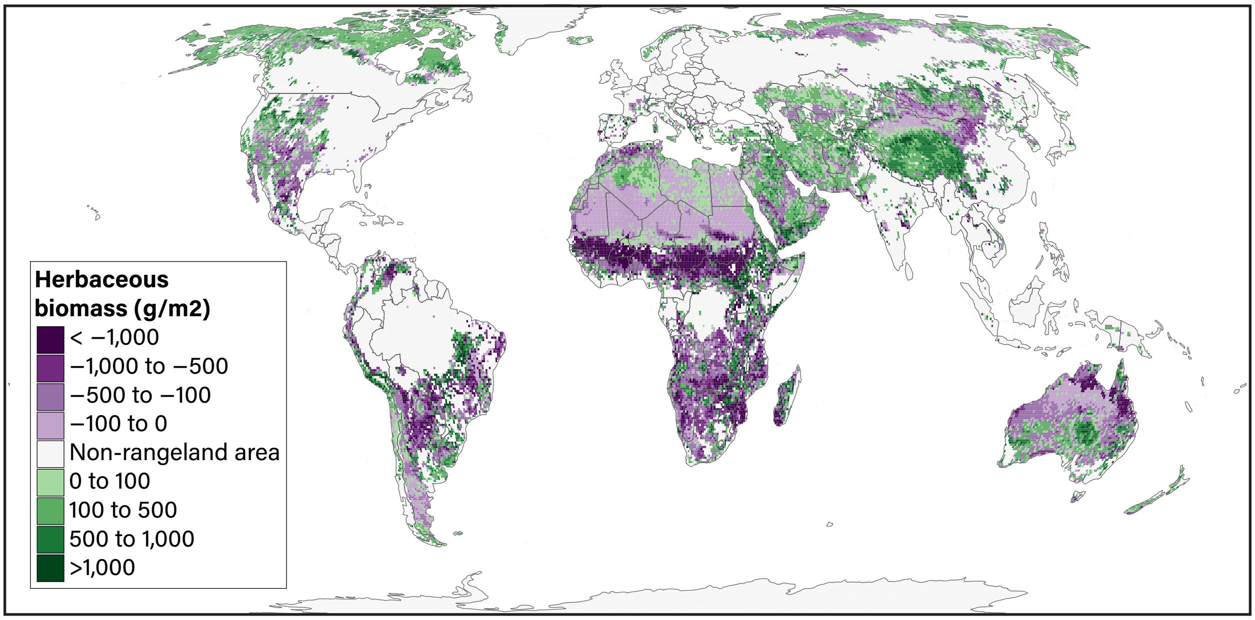
Without Carbon Fertilization

Due to shifts in monthly precipitation, as well as minimum and maximum temperature between 2017 and 2050 as projected by the general circulation models, we estimated that the world's rangelands will lose approximately 4 percent of their herbaceous biomass assuming no enhanced plant growth due to carbon fertilization.

The most consistent herbaceous biomass gains were in the northern latitudes near the Arctic in northern Canada, Alaska, Northern Europe, and Russia (figure 3). By contrast, the Sahelian region of Africa (that stretches across the continent) saw almost entirely losses. Other regions were expected to experience a combination of gains and losses, likely due in part to differences in elevation. For instance, the area of gains in Northern Africa corresponds with the Atlas Mountains, and high elevation areas of East Africa (such as the Ethiopian Highlands) would likely see gains as well. Similarly, the western coast of South America (which has areas of biomass gain) contains the Andean Mountain Range.

Figure 3

Projected difference in herbaceous biomass, without carbon fertilization, 2017–50



G/m2= grams per meter squared.

Note: Herbaceous biomass concentrations are estimated using the G-Range simulation model. Areas in white are not rangelands and are not modeled by G-Range.

Source: USDA, Economic Research Service using the G-Range simulation model using climate data from the GFDL-CM3 general circulation model (Donner et al., 2011).

Regions Gaining Biomass

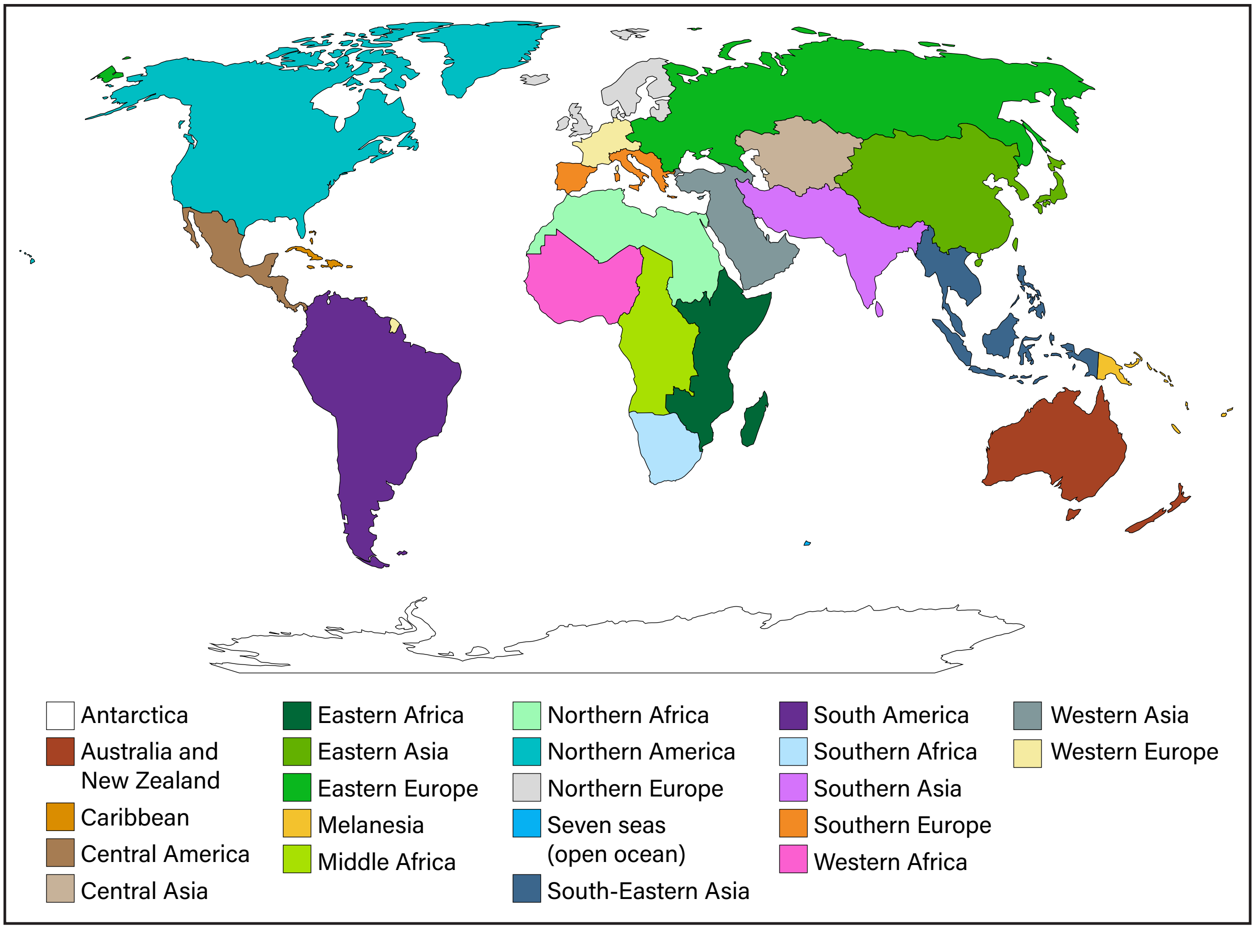
We present results by region and discuss some country-level results as well (figure 4). The following regions were estimated to gain herbaceous biomass (based on the mean of general circulation model results), even if no carbon fertilization occurs: the Caribbean, North America, Eastern Europe, Northern Europe, Western Europe, Central Asia, Eastern Asia, Southern Asia, Western Asia, and Melanesia. The largest percentage increases were estimated for Northern Europe (37 percent), Eastern Europe (21 percent), and North America (15 percent) (figure 5). The total quantity of herbaceous biomass varied greatly by region; because of this variation, the regions with the largest estimated absolute gain in herbaceous biomass were North America and Eastern Asia, followed by Eastern Europe (figure 6).

Results were not uniform within regions, and even regions that gained, on average, had some areas of loss. Within North America, Canada, Alaska, and Greenland had mostly gains, while the contiguous United States had a mix of gains and losses (figure 3). When results were aggregated at the country-level, Greenland would likely see gains of 86 percent of herbaceous biomass (the largest gain of any country). Canada was expected to see gains of about 45 percent, and the United States could experience much smaller gains of about 3 percent, on average. By contrast, Northern Europe and Eastern Europe had less variability, and most areas of these regions were expected to gain herbaceous biomass.

East Asia was dominated by China, where most areas of expected loss were in the northwestern part of the country. The eastern part of the country would likely see mostly gains. Central and Western Asia experienced a mix of gains and losses, and most countries in these regions could have net gains. Melanesia and the Caribbean are island regions, with very small quantities of herbaceous biomass.

Figure 4

Regional breakdown used in analysis

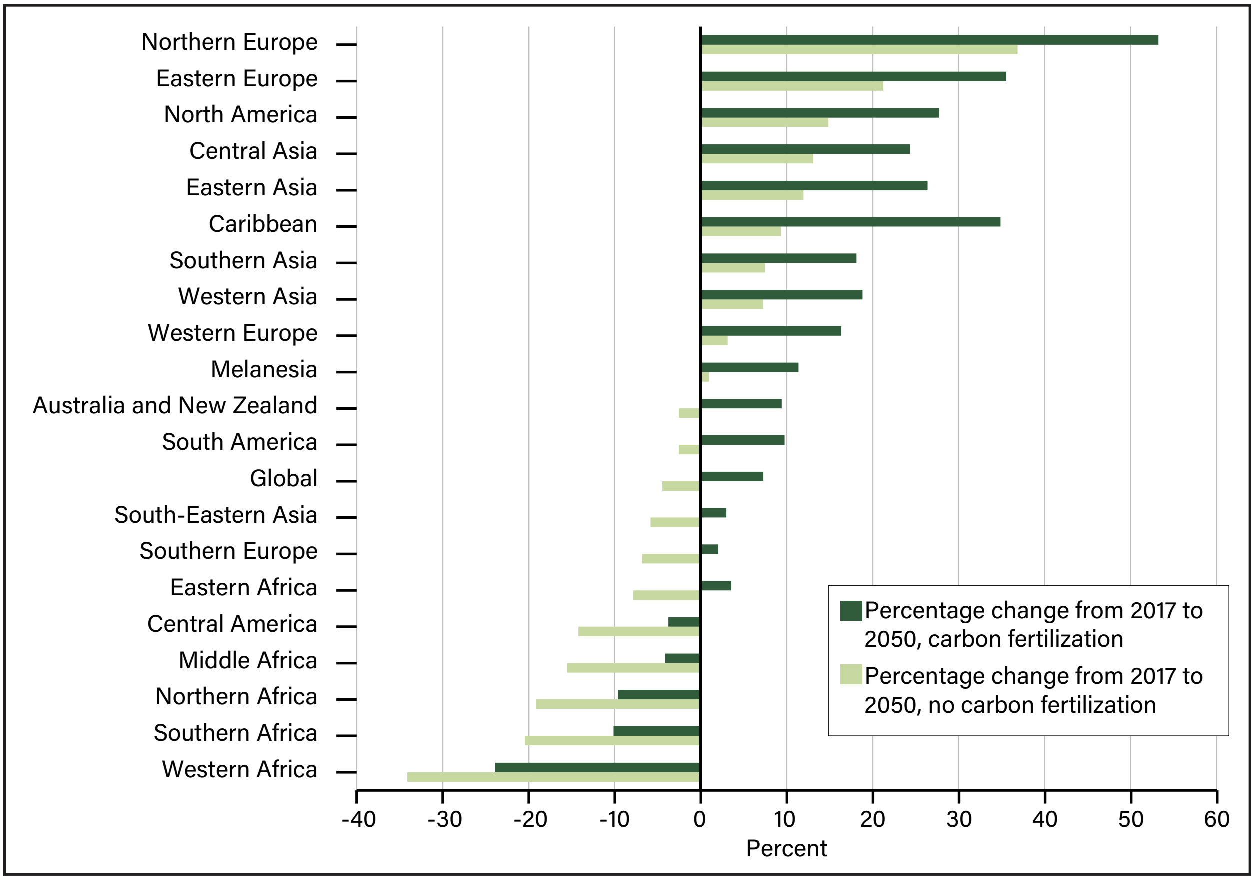


Note: French Guinea (geographically located in South America) is part of Europe in this regional breakdown because it is part of France. French Guinea has no rangeland biomass, so this does not affect results.

Source: USDA, Economic Research Service using Natural Earth public domain map data set.

Figure 5

Projected percentage change in herbaceous biomass by region, 2017–50



Note: Results are estimated from herbaceous biomass results, averaged across seven general circulation models.

Source: USDA, Economic Research Service using the G-Range simulation model with results averaged across seven general circulation models: HadGEM2.ES (Collins et al., 2011), IPSL-CM5A-LR (Dufresne et al., 2013), CSIRO-Mk3.6.0 (Collier et al., 2011), BCC-CMS 1.1 (Wu, 2012), GFDL-CM3 (Donner et al. 2011), GISS-E2-R (Schmidt et al., 2006), and MIR-CGCM3 (Yukimoto et al., 2012).

Regions Losing Biomass

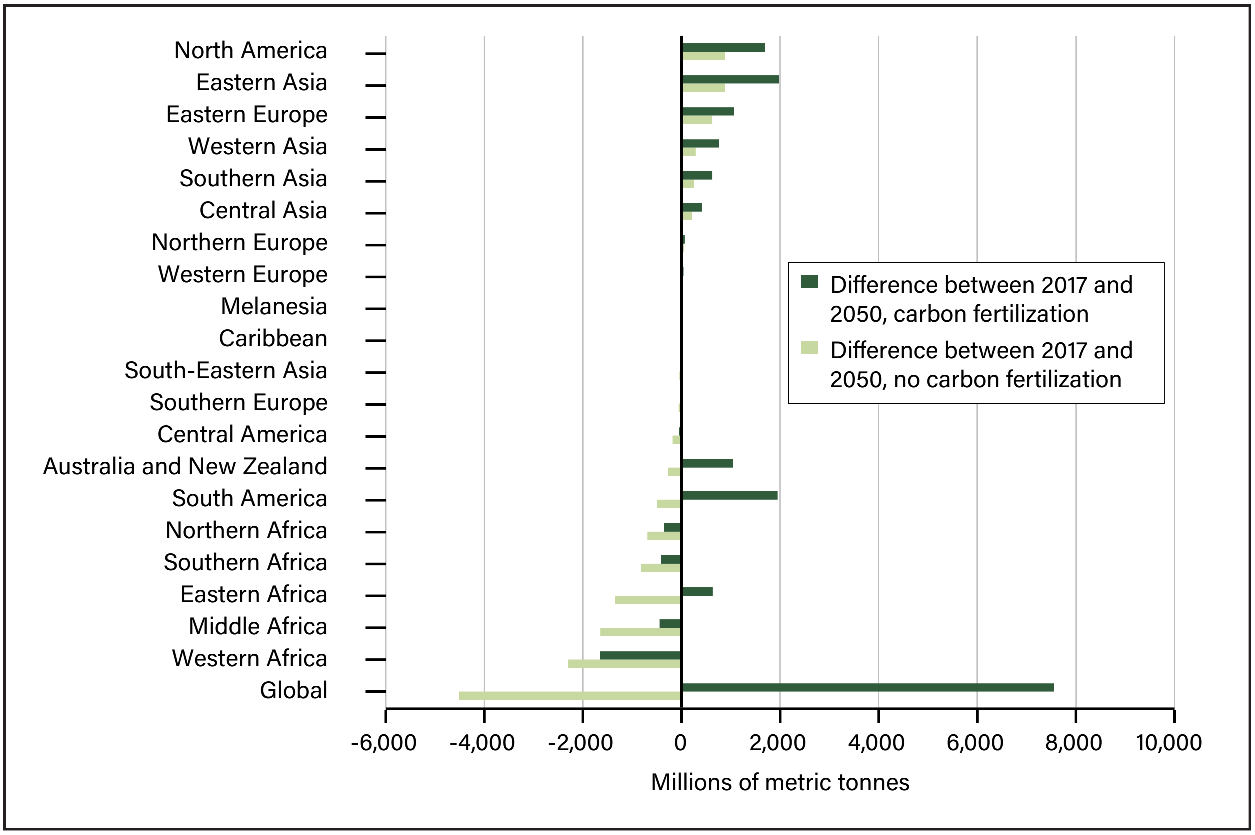
The model results show that several regions may experience herbaceous biomass loss. Africa fared poorly, potentially facing large losses in total and in percentage terms (figures 5 and 6). Estimates were the worst (within Africa and globally) for Western Africa, where 34 percent of herbaceous biomass was lost (figure 5). Except for very small areas of gain, almost all rangeland areas of Western Africa were estimated to lose herbaceous biomass. Other African regions had somewhat more variation, slightly mitigating their losses. As previously mentioned, the model projected some gains for Eastern and Northern African areas with higher elevation, although some mountainous countries like Ethiopia could see net losses. Very few African countries were likely to see net gains in herbaceous biomass: The highest gain was in Burundi at 14 percent.

Most of Central America's rangeland herbaceous biomass is located in Mexico, which was projected to lose close to 15 percent of its herbaceous biomass. Large areas of losses were estimated throughout Mexico, with small areas of gain in the northwestern region and even smaller areas throughout the rest of the country (figure 3). By contrast, South American rangelands, which could lose 3 percent of herbaceous biomass, cover many countries with a range of gains and losses. Brazil, Argentina, Venezuela, and Paraguay were each expected to lose about 4 to 7 percent of their herbaceous biomass. Brazil had a small area of potential strong gains in the northeastern part of the country, but otherwise, could experience mostly losses. The biggest gainers were Chile and Peru, which were projected to gain 34 percent and 25 percent, respectively. Some other countries could expect small gains, such as Columbia and Uruguay.

Finally, the region of Australia and New Zealand could see losses of 3 percent, with variation in gains and losses throughout both countries. New Zealand was expected to gain about 4 percent of herbaceous biomass, with some losses concentrated mostly in the south. Australia would likely lose about 3 percent of herbaceous biomass, with the greatest projected losses in the northern part of the country, coupled with some potential gains scattered throughout the southwestern and central part.

Figure 6

Projected change in total quantity of herbaceous biomass, 2017–50



Note: Results are estimated from herbaceous biomass results, averaged across seven general circulation models.

Source: USDA, Economic Research Service using the G-Range simulation model with results averaged across seven general circulation models: HadGEM2.ES (Collins et al., 2011), IPSL-CM5A-LR (Dufresne et al., 2013), CSIRO-Mk3.6.0 (Collier et al., 2011), BCC-CMS 1.1 (Wu, 2012), GFDL-CM3 (Donner et al. 2011), GISS-E2-R (Schmidt et al., 2006), and MIR-CGCM3 (Yukimoto et al., 2012).

With Carbon Fertilization

Globally, carbon fertilization of plants could completely offset losses that occur from changes in temperature and precipitation, resulting in a gain of approximately 7 percent of herbaceous biomass. All regions that gained biomass without carbon fertilization gained biomass with fertilization (figure 5). In addition, Australia and New Zealand, South America, South-Eastern Asia, Southern Europe, and East Africa, all regions that would lose biomass with no carbon fertilization, gained biomass as well. The remaining regions of Africa, as well as Central America, were expected to lose herbaceous biomass even with the benefits of carbon fertilization. The largest percentage increases accrued to Northern Europe, Eastern Europe, and the Caribbean, while the largest gainers in quantity of biomass were Eastern Asia, South America, and North America (figure 6).

While results were consistently higher under conditions with carbon fertilization, intraregional variation remained similar, as described above. For instance, Argentina and Brazil both gained about 8 percent of biomass with carbon fertilization, while Chile and Peru saw larger gains. Projected gains in Greenland (110 percent) and Canada (60 percent) continued to exceed those of the United States (15 percent).

Sensitivity of Results to General Circulation Models

Global results of different general circulation models varied by only a few percentage points: For no carbon fertilization scenarios, global losses ranged from 2 to 6 percent. For carbon fertilization scenarios, model results ranged from a gain of 3 to 10 percent (figures A.1, A.2). In general, general circulation model regional results showed more variation than global results. Results for the Caribbean and Central America had the greatest range across general circulation models, while South America had the smallest range for both results with and without carbon fertilization. Thus, sensitivity to the choice of general circulation model varies widely by region and demonstrates that there is uncertainty regarding climate models and how they will affect future plant growth.

Changes in Meat and Milk Production

With no carbon fertilization, our analysis estimated that annual global rangeland meat production would fall by only 0.01 percent and milk production would fall by 1 percent due to changes in herbaceous biomass availability from 2017 to 2050. Carbon fertilization could offset these small declines, leading to gains of up to 12 percent and 11 percent for meat and milk production, respectively. Global changes to beef and milk production were projected to be more positive than changes to herbaceous biomass. The reason was due to regional differences in herbaceous biomass shifts, the location of cattle raising, and variations in regional conversion factors of herbaceous biomass to beef and milk.

Because many areas of the world that had large increases in herbaceous biomass (particularly North America) had highly productive livestock sectors, the potential increases in herbaceous biomass translated to very large increases in beef and milk production (figure 7). By contrast, many regions with the greatest estimated percentage losses in herbaceous biomass, such as Western Africa, had less total herbaceous biomass and/or less productive livestock sectors; therefore, losses in biomass translated into smaller total losses in meat and milk production.

Our meat and milk estimates were based on potential production due to available biomass projected in 2017 and 2050. We relied on estimates obtained in previous literature regarding productivity parameters and cattle diet composition by region. Our production analysis considered that cattle obtain parts of their diet from nonherbaceous biomass sources; however, herbaceous biomass from nonrangeland areas (and rangeland areas where no cattle were present) were not accounted for. These parameters may have led to over-or-under estimates of total production, but they had a small effect on calculations of percentage change over time. For this reason, we focus most of our discussion on percentage changes to production rather than changes in magnitude.

Our estimate of the actual quantity of beef production in 2017 from rangeland herbaceous biomass was between 72 and 74 million metric tons, and for milk, it was between 3,000 and 3,500 million metric tons (depending on carbon fertilization). By comparison, according to the FAO, global beef production in 2017 was 64.3 million metric tons, and global production of cow's milk was 691 million metric tons (FAOSTAT, 2023b). Therefore, our analysis over estimated beef and milk production, particularly milk production. This may be because our milk estimates assumed every dairy cow is milked in all time periods, which is likely not realistic. In addition, our main analysis included areas that likely have very low densities of cattle: we partially addressed this by extending the analysis to only areas that have higher densities of cattle in a later section.

As with herbaceous biomass, results varied widely by region (figure 7). In general, regions that were estimated to lose rangeland herbaceous biomass would also lose meat and milk production, and regions that gained in rangeland herbaceous biomass would gain in production as well.

The regions that were expected to lose the most meat and milk production were in Africa, as well as Central America. As with herbaceous biomass results, there was intraregional variation. While most African countries (particularly West African countries) would see losses in meat and milk production, the worst off were Mauritania, Burkina Faso, Senegal, Mali, and Chad (all located in West Africa)—which were all projected to lose more than 50 percent of meat and milk production without carbon fertilization. By contrast, Nigeria and Sierra Leonne (which are also located in West Africa) were projected to lose 22 percent and gain 7 percent of meat and milk production (also without carbon fertilization), respectively. In Central America, Mexico was projected to experience a 16-percent loss. By contrast, Guatemala was expected to gain about 15 percent. Most other Central American countries were not included in the analysis because they do not have cattle production on rangelands.

Other regions that were expected to lose meat and milk production without carbon fertilization were Eastern Africa, Southern Europe, Southeast Asia, South America, and Australia and New Zealand. New Zealand fared slightly better than Australia: New Zealand was expected to have small gains (4 percent) without carbon fertilization, while Australia was expected to lose about 2 percent. In Southeast Asia, Laos was expected to lose 28 percent (the largest in Southeast Asia), followed by Cambodia and Thailand. Other countries in the region were expected to see small losses or small to moderate gains. In South America, small losses of less than about 10 percent were expected in Brazil, Argentina, Venezuela, Bolivia, and Paraguay. Expected gains would be slightly higher in Colombia and Uruguay. Large gains in production (about 25 percent) were expected in Peru and Chile. In Southern Europe, which has little rangeland cattle production, most potential losses accrued in Portugal; other countries saw smaller changes. Scenarios with carbon fertilization predicted that each of these regions would gain in production from about 1 percent for Southern Europe to about 10 percent for Australia and New Zealand.

Remaining regions were estimated to gain in meat and milk production, even without carbon fertilization. These regions included all European regions outside of Southern Europe. Most individual countries in these European regions were estimated to gain in production: Increases were particularly large in Austria and Slovenia, with more than 50 percent gain without carbon fertilization. Eastern European results were dominated by Russia, as most other countries included in this region were small and many had no rangeland cattle production.

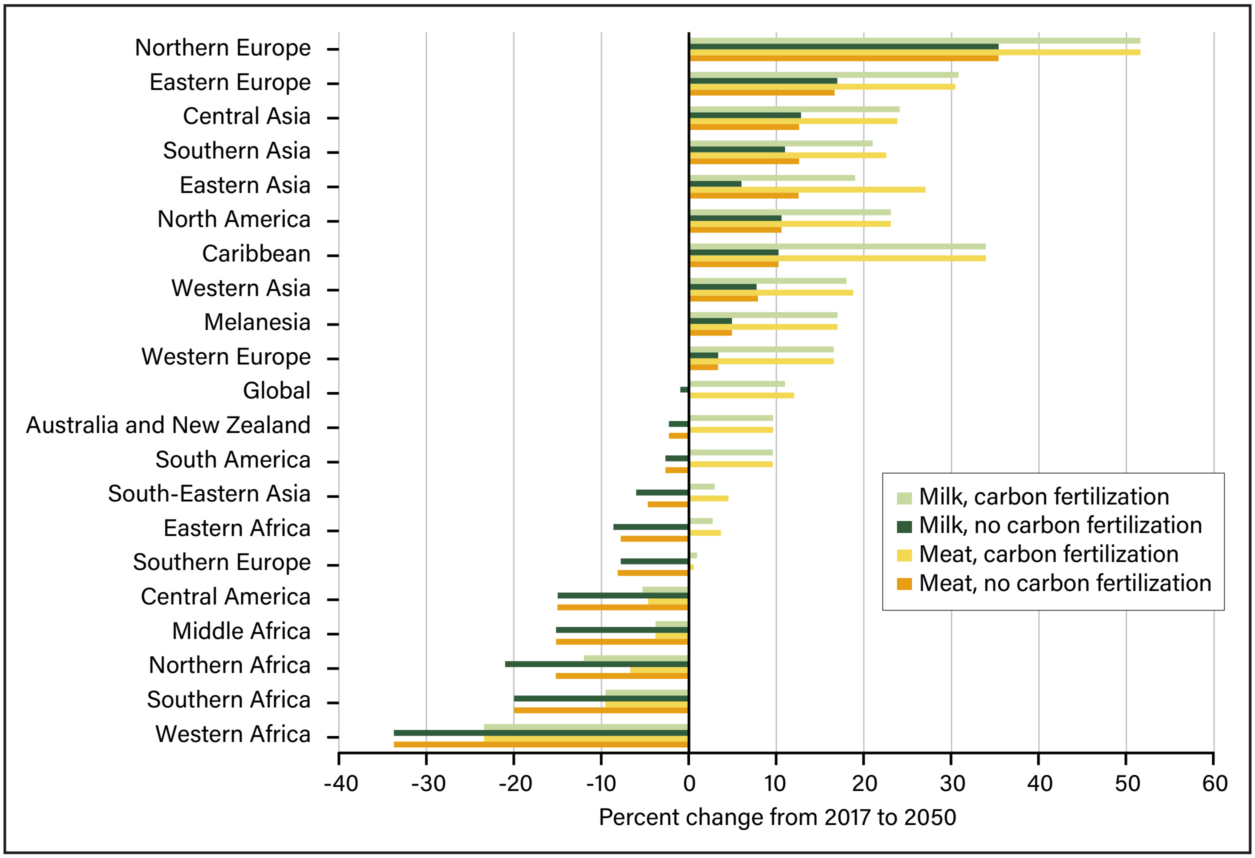
Several Asian regions were also estimated to gain production: Central Asia, Southern Asia, Eastern Asia, Western Asia, and Melanesia. The small, mountainous Southern Asian countries of Nepal and Bhutan were expected to have the highest percentage gains in all of Asia (above 40 percent gain in meat production with no carbon fertilization). By contrast, Pakistan, (also located in Southern Asia) was estimated to have gains of 2 percent.

Finally, North America and the Caribbean were also anticipated to see gains. While the Caribbean has little rangeland meat production, North America was a top-producing region and the largest expected gainer globally in total meat and milk production. Percentage gains in Canada were much higher than in the United States: Without carbon fertilization, Canada was expected to gain almost 50 percent of beef and milk production, while the United States would gain only 2 percent of production without fertilization. This result was not surprising, as most of northern Canada was expected to gain herbaceous biomass (figure 5).

By contrast, the biomass map of the United States was spotty: Some areas would gain and some would lose. Greenland, which is part of North America and expected to have large increases in herbaceous biomass, does not have rangeland cattle production, so Greenland was not included in the production estimates.

Figure 7

Projected percent change for meat and milk production, 2017–50



Note: Results shown are averaged across seven general circulation models. Percentage change is calculated as the difference between each region's 2050 and 2017 meat or milk production, attributable to its herbaceous biomass on rangelands where cattle reside, divided by the region's 2017 meat or milk production, attributable to its herbaceous biomass on rangelands where cattle reside, multiplied by 100.

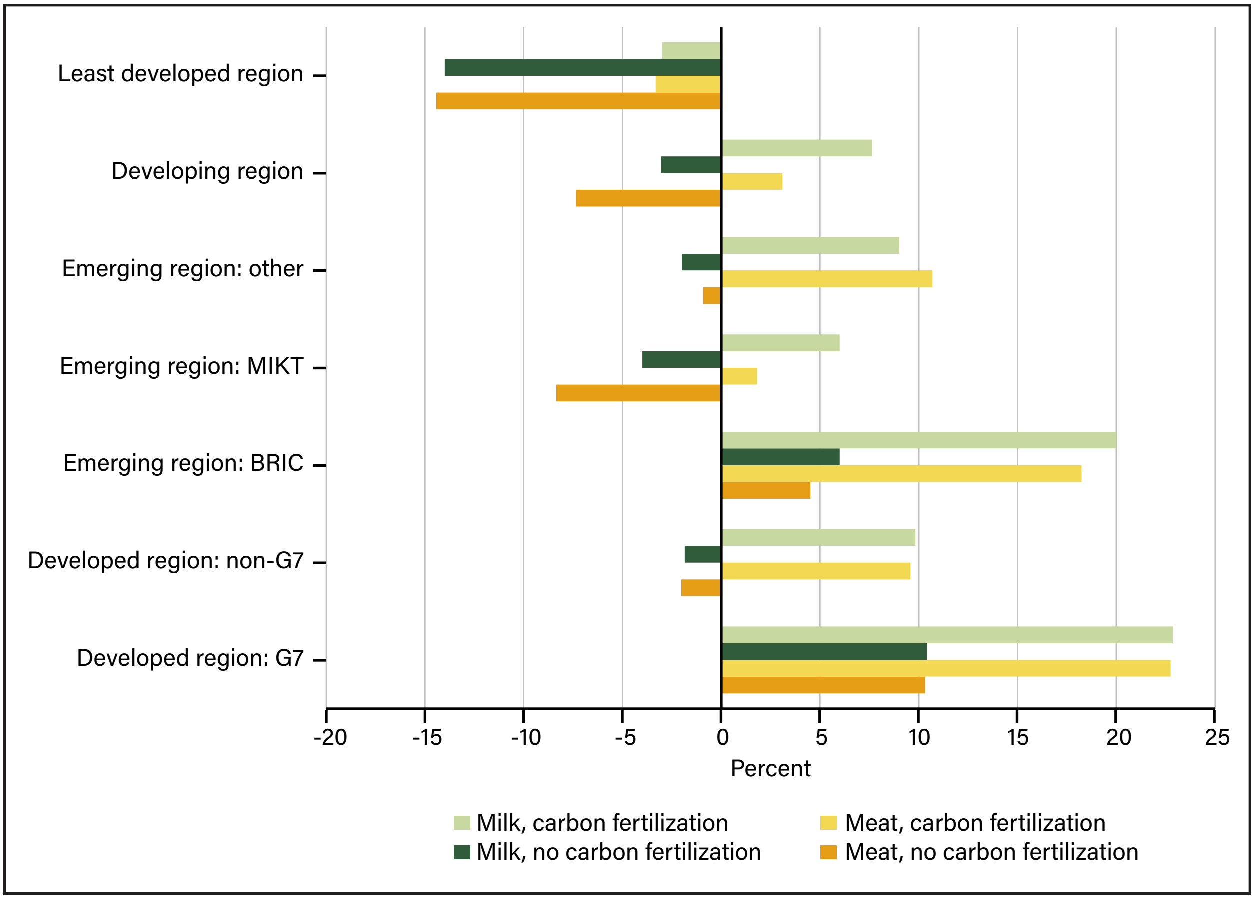
Source: USDA, Economic Research Service using the G-Range simulation model with results averaged across seven general circulation models: HadGEM2.ES (Collins et al., 2011), IPSL-CM5A-LR (Dufresne et al., 2013), CSIRO-Mk3.6.0 (Collier et al., 2011), BCC-CMS 1.1 (Wu, 2012), GFDL-CM3 (Donner et al., 2011), GISS-E2-R (Schmidt et al., 2006), and MIR-CGCM3 (Yukimoto et al., 2012).

Results by Level of Economic Development

When results were examined by the level of economic development, distributional production impacts of climate change on herbaceous biomass were estimated to be substantial. Developed G7 countries (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States) had the highest gains to meat and milk production with or without the benefit of carbon fertilization (figure 8). BRIC countries (consisting of Brazil, Russia, India, and China) were also estimated to gain meat and milk as a group, while results were mixed for other emerging and developing regions. However, the least developed region (which consists of countries primarily in Africa and Asia) was estimated to lose meat and milk production, even with the benefit of carbon fertilization.

Figure 8

Projected meat and milk production percentage change, 2017–50



MIKT = Mexico, Indonesia, South Korea, and Turkey. BRIC = Brazil, Russia, India, and China. G7 = Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States.

Note: Results shown are averaged across seven general circulation models. Percentage change is calculated as the difference between each region's 2050 and 2017 meat or milk production, attributable to its herbaceous biomass on rangelands where cattle reside, divided by the region's 2017 meat or milk production attributable to its herbaceous biomass on rangelands where cattle reside, multiplied by 100.

Source: USDA, Economic Research Service using the G-Range simulation model with results averaged across seven general circulation models: HadGEM2.ES (Collins et al., 2011), IPSL-CM5A-LR (Dufresne et al., 2013), CSIRO-Mk3.6.0 (Collier et al., 2011), BCC-CMS 1.1 (Wu, 2012), GFDL-CM3 (Donner et al., 2011), GISS-E2-R (Schmidt et al., 2006), and MIR-CGCM3 (Yukimoto et al., 2012).

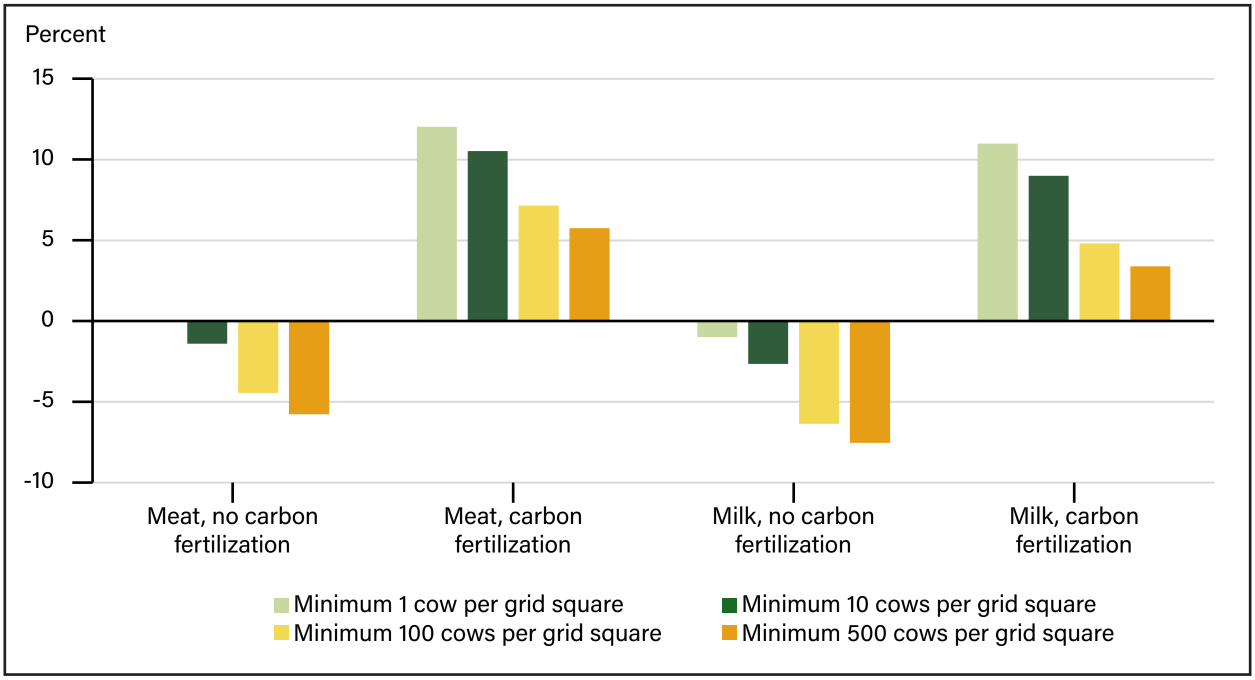
Results by Level of Cattle Density

The previous results for meat and milk production considered all herbaceous biomass that was grown anywhere on rangelands where any cattle were located, according to the Gridded Livestock of the World (GLW) 2015 (Gilbert et al., 2022). However, some of these areas have very low densities of cattle. We estimated changes in beef and milk production by limiting the geographic areas considered to those with greater cattle densities. While the original results considered all areas with at least 1 cattle per pixel, here we examined results for areas with a minimum of 10 cattle, 100 cattle, and 500 cattle per pixel. This check allowed us to examine how production may change due to shifts in herbaceous biomass in areas with greater cattle concentrations.

As the minimum density of cattle increases, the effects of climate change on meat and milk production became worse globally (figure 9). Without carbon fertilization, meat production was estimated to decline by 1 percent in areas with a density of least 10 cows, 4 percent in areas with at least 100 cows, and 6 percent in areas with at least 500 cows. With carbon fertilization, we estimated that each of these areas would gain in meat production, but those gains would decline from 12 percent in areas with at least 1 cow to 6 percent in areas with at least 500 cows. Results for milk were similar: We estimated losses of 8 percent in areas with at least 500 cows. With carbon fertilization, we estimated that gains will drop from 11 percent in areas with at least 1 cow to 3 percent in areas with 500 cows.

Figure 9

Projected global changes in meat and milk production by cattle density, 2017–50



Note: Results shown are averaged across seven general circulation models. Percentage change is calculated as the difference between each region's 2050 and 2017 meat or milk production, attributable to the region's herbaceous biomass on rangelands where cattle reside, divided by the region's 2017 meat or milk production, attributable to its herbaceous biomass on rangelands where cattle reside, multiplied by 100.

Source: USDA, Economic Research Service using the G-Range simulation model with results averaged across seven general circulation models: HadGEM2.ES (Collins et al., 2011), IPSL-CM5A-LR (Dufresne et al., 2013), CSIRO-Mk3.6.0 (Collier et al., 2011), BCC-CMS 1.1 (Wu, 2012), GFDL-CM3 (Donner et al., 2011), GISS-E2-R (Schmidt et al., 2006), and MIR-CGCM3 (Yukimoto et al., 2012).

Results tended to worsen in nearly all regions as cattle density increased. The largest estimated changes were in Northern Europe, Eastern Europe, and North America. The reason was likely because each of these regions has areas of low cattle density at northern latitudes that gain herbaceous biomass (figures 2 and 3). For instance, in North American areas with at least one cow, we estimated that the area's potential beef production would increase by 11 percent. This number declines to 7 percent in areas with at least 10 cows. In areas with at least 100 cows, we estimated that the region would lose 2 percent of meat production; in areas with at least 500 cows, it was expected to lose about 1 percent of production. In Northern Europe, estimated gains in meat production dropped from 35 percent to 18 percent, and in Eastern Europe, gains fell from 17 percent to 1 percent as minimum cattle densities increased from 1 cow to 500 cows. However, some regions could see smaller changes; for instance, South American declines remained at about 3 percent regardless of the level of cattle density.

For the regions that were expected to lose the most meat production due to losses in herbaceous biomass, results were mixed as cattle density increased. Western African production declines increased by only a few percentage points: from 34 percent to 37 percent. Southern African and Central American losses were mitigated somewhat. For Northern Africa and Middle Africa, losses increased from a decline of about 15 percent each to 22 percent and 25 percent, respectively.

This analysis indicates that globally (and across many regions), areas with relatively higher cattle density are likely to do worse relative to areas with low cattle density. This finding is partly because many areas with low cattle densities, such as in northern latitudes, are expected to gain large quantities of herbaceous biomass.

Conclusion

Globally, changes in herbaceous biomass, meat production, and milk production may range from small losses to moderate gains. Without carbon fertilization, this study estimates that herbaceous biomass would decline by 4 percent, meat production would remain about the same, and milk production would decrease by about 1 percent. With carbon fertilization, herbaceous biomass could increase by as much as 7 percent, leading to gains for meat and milk production: 12 and 11 percent respectively. Results were more positive for meat and milk production compared to herbaceous biomass. The reason is, in part, because some regions that are highly productive in animal products (particularly North America) were predicted to have large gains in biomass, and therefore, production.

Global aggregations mask larger losses experienced by several regions. The poorest regions are likely to be most negatively affected. The largest losses were projected to be in Western Africa, potentially losing around 34 percent of its herbaceous biomass without carbon fertilization. Other African regions were expected to lose biomass, meat, and milk production as well. The estimated losses in Africa are especially concerning considering current projections that the continent will likely experience a large increase in demand for animal-source food products in the coming decades. Total demand for red meat, poultry, dairy, and eggs is expected to increase 155 percent in Sub-Saharan Africa between 2020–50, the highest of any region, due to population growth, rising incomes, and shifts in consumer preferences (Komarek et al., 2021).

Other regions were expected to experience gains, including Northern Europe, Eastern Europe, and North America. However, it is important to note that there was intraregional variation in results; for instance, within North America, Canada was expected to have much higher production gains than the United States, where gains would be modest. Overall, this study helps highlight the potential distributional effects of climate change on herbaceous biomass, meat, and milk production. When results were examined by development group, the largest anticipated losses accrued in developing and least developed countries, while developed countries were likely to experience gains or smaller losses.

This study also shows that areas that currently have greater concentrations of cattle will likely suffer disproportionately from herbaceous biomass loss due to climate change. When the analysis was restricted to areas with greater cattle concentration, results worsened globally and in most regions. This result suggests that pressure from climate change may be greatest in areas of high cattle concentrations and highlights that many areas predicted to have large gains in herbaceous biomass currently have very low cattle concentrations. This finding may indicate an avenue for adaptation: relocation of cattle populations to areas more likely to gain herbaceous biomass, such as those at northern (or southern) latitudes and higher elevations.

Our results are consistent with other literature. Boone et al. (2018) and Godde et al. (2020) also estimated there will be small global changes to herbaceous biomass with large regional differences, with the worst outcomes occurring in Africa. While Godde et al. (2020) did not estimate changes to meat and milk production, they found that herbaceous biomass losses were worse in areas with low levels of cattle productivity, as do our results, and that biomass loss was associated with high levels of poverty. Boone et al. (2018) estimated that biomass loss due to climate change would cause a 7.5- to 9-percent reduction in livestock units, globally. Our results may be more positive for meat and milk production because we considered more varying regional parameters in estimating production losses. We also expanded on their production estimates by providing regional-level results.

In general, this study did not consider adaptive capabilities of cattle raising populations, although many may arise, particularly in the regions most affected by loss of herbaceous biomass. By holding production parameters constant between 2017 and 2050, we did not allow for technological or production changes that would change cattle productivity over time. Given the large regional variation in parameters such as feed efficiency, there may be opportunities for lagging regions to increase productivity. We also did not allow for any management practices like rotational grazing that may help conserve herbaceous biomass in vulnerable areas, shifts in where production is located, or shifts in production systems away from grazing and toward landless production. Any of these adaptations may occur, as well as shifts toward more climate-resistant breeds of cattle or different species, such as goats that could be less vulnerable to herbaceous biomass loss. In addition, our regional results did not account for the possibility of interregional trade of herbaceous biomass, which could potentially alleviate some interregional variation of gains and losses in meat and milk production. Results suggested that in certain regions, such as Africa where demand is expected to rise, mismatches in demand and supply of beef and milk may emerge in coming decades. This development could spur increases in prices for these products and/or imports.

Our study is limited in that it captured only one specific way that climate change may impact livestock production. G-Range estimates change in herbaceous biomass due to general circulation model projections of monthly minimum and maximum temperatures and average monthly rainfall. Results are reliant on general circulation model climate projections and correct assumptions regarding carbon fertilization; we dealt with this uncertainty by averaging several general circulation model results together and simulating models with and without carbon fertilization. However, if climate change affects herbaceous biomass in other ways (such as through changing wildfire patterns, plant diseases, or herbaceous biomass quality), these effects are not captured in our results. We also only accounted for changes in rangelands where cattle are present, limiting the scope of our analysis.

As temperatures rise and rainfall patterns change, heat stress can affect animals directly, pathogen spread may rise, and reduced availability of water can threaten animals' health. These other effects may be large; for instance, previous literature estimates that, by midcentury, heat stress will reduce global meat and milk production by 7 and 2 percent, respectively (Thornton et al., 2022). This finding indicates that heat stress may have a larger overall effect on production than climate driven changes in herbaceous biomass. The changes are expected to result in a mix of gains and losses, depending on location. In addition, according to our results and previous literature, the same regions that suffer the most from loss of biomass will also suffer the most from heat stress: Mainly areas that have warm and/or humid climates, especially Africa. Thus, some producers will be hit with multiple climate stressors, which may make productivity advances and adaptation more difficult. Future research is needed to evaluate the many ways climate change can affect livestock production, and how producers can adapt.

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Appendix

Table A.1

Full general circulation model herbaceous biomass percentage projected change results for no carbon fertilization scenarios, 2017–50

Region	HDG	IPS	CSI	BCC	GFD	GIS	MRC
Eastern Africa	-12.22	-5.51	-12.99	-5.51	-6.05	-9.15	-5.51
Middle Africa	-16.79	-16.89	-16.26	-15.15	-17.99	-10.31	-14.12
Northern Africa	-23.49	-20.21	-23.73	-14.44	-18.39	-18.17	-17.37
Southern Africa	-20.19	-21.60	-26.22	-20.84	-18.11	-14.12	-21.91
Western Africa	-41.73	-44.37	-38.49	-26.02	-36.99	-25.05	-25.22
Caribbean	-4.92	2.44	8.44	1.75	-4.16	16.78	51.02
Central America	-10.06	-32.78	-11.03	-13.52	-11.73	-5.38	-20.01
Northern America	17.57	16.57	10.84	12.62	20.95	12.34	14.40
South America	-2.54	-4.29	-2.22	-2.33	-4.83	-0.31	-0.57
Central Asia	16.97	3.15	5.50	5.81	15.36	17.77	21.83
Eastern Asia	14.72	13.86	6.25	9.09	16.85	12.01	10.22
Southeastern Asia	-0.94	-3.97	-7.93	-7.80	-4.09	-8.36	-7.26
Southern Asia	3.97	2.30	5.92	6.98	9.73	10.54	14.37
Western Asia	4.34	5.85	4.95	5.37	11.60	6.25	12.91
Eastern Europe	27.07	27.17	18.69	18.21	13.75	21.29	23.78
Northern Europe	39.94	43.68	26.96	42.97	39.25	27.33	41.23
Southern Europe	-6.09	-5.12	-10.38	-6.89	-8.84	-6.45	-3.81
Western Europe	0.69	9.56	0.12	3.18	1.21	3.31	5.42
Australia and New Zealand	-6.58	-4.11	-10.79	1.00	-5.92	5.08	6.16
Melanesia	0.55	6.32	3.50	-0.63	0.45	-0.06	-2.99
Global	-6.09	-5.64	-8.26	-3.85	-4.30	-2.05	-1.89

HDG = HadGEM2.ES (Collins et al., 2011). IPS = IPSL-CM5A-LR (Dufresne et al., 2013). CSI = CSIRO-Mk3.6.0 (Collier et al., 2011). BCC = BCC-CMS 1.1 (Wu, 2012). GFD =GFDL-CM3 (Donner et al., 2011). GIS = GISS-E2-R (Schmidt et al., 2006). MRC= MIR-CGCM3 (Yukimoto et al., 2012).

Source: USDA, Economic Research Service using the G-Range simulation model.

Table A.2

Full general circulation model herbaceous biomass percentage change projected results for carbon fertilization scenarios, 2017–50

Region	HDG	IPS	CSI	BCC	GFD	GIS	MRC
Eastern Africa	-1.12	6.05	-1.83	6.16	5.17	2.38	6.21
Middle Africa	-5.59	-6.02	-4.40	-4.23	-7.47	2.59	-2.92
Northern Africa	-15.42	-10.10	-14.92	-4.29	-8.31	-8.59	-7.39
Southern Africa	-9.69	-11.05	-16.20	-10.66	-8.30	-2.87	-12.00
Western Africa	-31.68	-35.41	-29.04	-15.16	-26.99	-14.35	-13.73
Caribbean	-1.95	6.29	45.08	7.09	42.60	58.70	80.56
Central America	1.14	-24.82	-0.05	-3.93	-1.15	7.17	-10.31
Northern America	30.43	29.54	23.45	25.01	34.63	25.16	27.29
South America	10.07	7.21	10.33	9.95	7.03	12.53	11.97
Central Asia	28.44	14.09	15.64	16.14	27.76	29.53	33.44
Eastern Asia	29.56	28.68	20.06	23.46	32.03	26.31	24.08
Southeastern Asia	7.03	5.13	1.70	1.50	3.46	1.19	1.08
Southern Asia	14.19	12.84	16.28	17.68	21.00	21.33	25.14
Western Asia	15.55	17.60	15.98	16.81	23.87	17.41	24.81
Eastern Europe	41.62	42.02	32.65	32.41	27.54	35.79	37.84
Northern Europe	56.88	60.87	42.30	60.74	55.75	42.26	58.06
Southern Europe	3.12	4.42	-1.86	2.15	0.06	2.45	4.29
Western Europe	13.39	24.28	12.54	17.05	14.16	16.28	18.32
Australia and New Zealand	5.23	7.69	0.88	12.66	6.27	16.92	18.62
Melanesia	10.13	17.58	13.21	10.49	10.98	9.57	8.22
Global	5.62	5.92	3.32	7.87	7.45	10.08	10.03

HDG =HadGEM2.ES (Collins et al., 2011). IPS =IPSL-CM5A-LR (Dufresne et al., 2013). CSI =CSIRO-Mk3.6.0 (Collier et al., 2011). BCC = BCC-CMS 1.1 (Wu, 2012). GFD = GFDL-CM3 (Donner et al., 2011). GIS = GISS-E2-R (Schmidt et al., 2006). MRC = MIR-CGCM3 (Yukimoto et al., 2012).

Source: USDA, Economic Research Service using the G-Range simulation model.