An Integrated Study of Climate Change Impacts on the U.S. Livestock Sector

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1. Introduction

The United States is the world's largest producer of beef and poultry, the second largest milk producer, and the third-largest producer of pork products (US Department of Agriculture, National Agricultural Statistics Service 2021). Livestock and poultry typically account for over half of U.S. agricultural cash receipts, with a total value exceeding $160 billion per year (US Department of Agriculture, Economic Research Service 2022). As the primary provider of protein, livestock products have been facing rapid growth in demand, and this increasing trend is expected to continue in the following decades.

However, future livestock production is likely to be affected by climate change, either directly through the loss of production or indirectly through resource use and resource competition (Thornton et al. 2009). Figure 1 shows the two types of impacts of climate change on livestock. The direct impacts mainly come from heat stress, the magnitude of which is affected by the ambient temperature, humidity, animal species, and living conditions (Rojas-Downing et al. 2017). As the future climate is projected to be warmer and there will more variations in the precipitation patterns, heat stress threat may expand its influence and impose great challenges on livestock section. A variety of studies have found that heat stress directly affects livestock through animal production performance, reproduction, health conditions, and mortality rates (Bishop-Williams et al. 2015; Fan 2018; Bagath et al. 2019; Wang and McCarl 2021; Cheng, McCarl and Fei 2021).

The livestock section is not only impacted by climate change through its own production rate, but also through the input side, which is referred to as the indirect impact in many related studies

(Collier et al. 2019). The indirect impacts comes from the climate change-induced crop and pasture yield, water and land use, and the resulted feed cost and land need changes. Around 58% of the global biomass harvested worldwide are used as feed for livestock (Krausmann et al. 2008). The elevated atmospheric CO_2 level and temperature may lead to changes in forage quantity and quality, as well as the length of growing seasons (Polley et al. 2013). As forage quantity and quality decrease, more resources might be needed to satisfy livestock feed requirements. The increasing demand for livestock products imposes a higher demand for resource usage, including forage, water, and land. These all add to the climate change impact on livestock production through competition for natural resources.

Although the livestock sector is facing significant challenges from the changing climate, not much attention has been paid to the vulnerability of the livestock sector under climate change. There exists a vast research gap in the studies of the integrated impacts of climate change on the livestock sector and potential adaptation strategies to cope with climate change impact on the livestock sector. In this research, we will fill the gaps in the literature by making a comprehensive analysis of climate change impact on the US livestock sector, investigating the adaptation alternatives, the consequential market responses, and the impacts on the consumers' and producers' welfare.

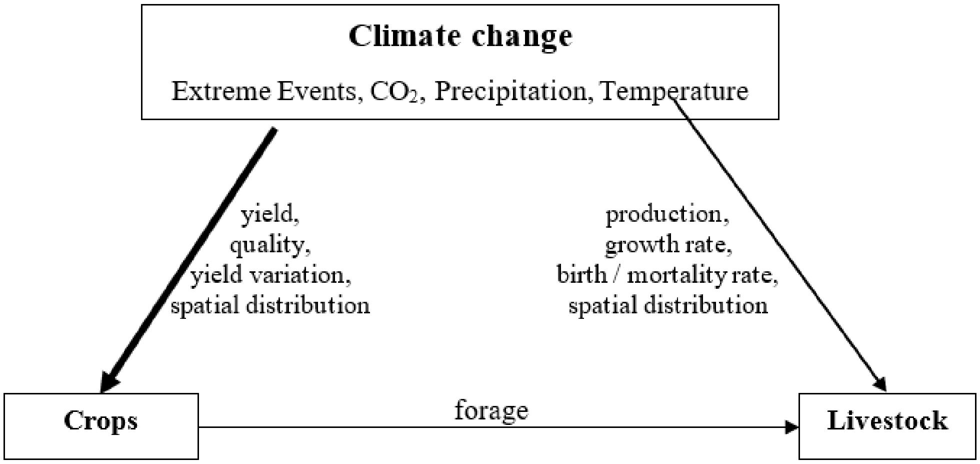

Figure 1: Climate change impacts on livestock

2. Literature Review

For the past few decades, climate change has imposed significant impacts on agricultural production, and it along with its drivers are projected to expand in influence with increasing temperature, more variation in precipitation patterns, more frequent extreme climate events and rising concentrations of carbon dioxide (Klein et al. 2014). Impacts of climate change on agriculture production involve alterations in agricultural productivity and variability, water usage and availability and production cost (pesticide, energy, etc.) (Chen and McCarl 2001; Reilly et al. 2003; Hatfield and Dold 2019).

Climate change implications for livestock production have been studied and are getting increasing attention in recent years (Hristov et al. 2018; Rust 2019). Most of the studies on climate change impacts on livestock are focusing on the direct physical impacts which mainly come from heat stress (Ayo, Obidi and Rekwot 2011; Brown-Brandl 2018; Bagath et al. 2019; Thornton et al. 2021). Heat stress results from the ambient temperature exceeding animals' thermal comfort zone and animals' incapable of dissipating sufficient heat to maintain homeothermy (West 1999). Animals have their own adaptive mechanisms to keep heat homeostasis, including changes in respiration rate, pulse rate, rectal temperature, sweating rate, and skin temperature (Rashamol et al. 2020). However, as adaptive mechanisms try to re-establish homeothermy, animals' productive and reproductive performance are compromised because extra energy is needed to survive in harsh environmental conditions. The impaired performance includes a decrease in weight gain per unit of feed energy, daily weight gain, milk and egg yield, and a decline in reproduction efficiency (Rojas-Downing et al. 2017).

In terms of the indirect impacts of climate change on livestock production, climate change indirectly influences livestock production through the effects on feed production, water availability, and pest/pathogen populations (Rojas-Downing et al. 2017; Collier et al. 2019). The majority of the literature focuses on crop productivity and associated economic implications. This literature segment finds that changes in the climate have had spatially heterogeneous and crop-specific effects on yields, which lead to production and welfare changes (Leng and Huang 2017; Kukal and Irmak 2018). Additionally, various findings on crop yield and variability have arisen regarding the effect of altered temperature and precipitation (McCarl, Villavicencio and Wu 2008; Schlenker and Roberts 2009; Troy, Kipgen and Pal 2015). Studies have also shown that atmospheric carbon dioxide (CO2) concentration increases affect crop yield and plant physiology (such as photosynthesis and pigment production) with larger effects on C3 species (soybeans, cotton and wheat) relative to C4 species (corn and sorghum) (Attavanich and McCarl 2014; Ziska 2016). Furtehrmore, extreme climate events impact crop yields with effects varying seasonally, spatially and by crop (Carlson, Todey and Taylor 1996; Lobell et al. 2013; Troy et al. 2015). These studies have shown that climate change affects the feed and forage consumed by livestock, but to what extent livestock production is influenced has not been separately investigated.

Regarding livestock species, climate change related research has an emphasis on ruminants and monogastric livestock such as pigs and poultry get much less consideration (Escarcha, Lassa and Zander 2018). Cheng et al. (2022) reviewed 159 publications on livestock and climate change subjects and 55% of them focused on ruminants, and cattle is the most studied species (30% of total publications). One of the reasons might be that ruminant livestock is generally more dependent on the environment in which they live for feed and receive impacts directly from the climatic variations, while animals raised by an intensive production system are thought to be less vulnerable to climate. Following the studies on beef, cattle and dairy production (e.g. Collier and Zimbelman 2007; Key and Sneeringer 2014), we extended the climate change impact research to hog and chicken (Cheng 2022) and found that their production and reproduction performance are also susceptible to climate change even if they are kept in the confined livestock buildings. This indicates that the total impact of climate change on the livestock production could be greater than people used to believe, which means our research needs to be moved beyond the scope of a single species to properly estimate the climate change impacts.

Moreover, although some efforts have been made to examine the climate change impacts on the U.S. livestock sector (e.g., St-Pierre, Cobanov and Schnitkey (2003)), existing studies barely consider the feed cost and other production inputs in the analysis. For example, in the southern U.S. where the climate is projected to be hotter and drier in the future (Masson-Delmotte et al. 2021), the yield of forage and hays may decrease, which in turn may lead to an increase in the potential land use/cost by a certain amount of pasture animals. Also, as the crop planting area moves northward and eastward to cooler areas to cope with climate change (Fei, McCarl and Thayer 2017), the direct feed cost and the transportation cost of feed would rise and result in an elevation of the total input cost in the livestock sector. We failed to find quantitative studies that thoroughly investigated the integrated impact of climate change with inclusion of the relationship between livestock and crops. Herein our study aims to fill this knowledge gap.

In response to the direct and indirect impacts of climate change on livestock performance and operation costs, adaptative reactions have already taken place. For example, Zhang et al. (2013) found that the intensity of summer heat stress can lead to significant changes in the spatial distribution of cattle breed mix in Texas. Other studies also suggest changes in livestock breed mix (Hayes, Lewin and Goddard 2013; Barendse 2017) and location (Wang and McCarl 2021) as adaptation strategies to climate change. However, climate impacts vary by species and regions, and there still remain significant uncertainties as to future climate (Godde et al. 2021). Therefore the adaptation measures are expected to account for a wide range of potential scenarios and it is our intention to investigate the optimal adaptation strategies under different climate change contexts.

3. Methods and Data

This study examines the economic impacts of climate change across the major us livestock types: beef and dairy cattle, hogs, and chickens, along with considering the effects on grazing lands and feed supplies. To do this, we pursue a three-pronged study which is shown in Figure 2. First, we estimate econometric models for animal production and performance for several previously overlooked livestock and crop yield cases plus extend estimations done in other studies. Second, we use our estimated coefficients to project climate change impacts on these measures. Finally we use an agricultural sector model to simulate the impacts of projected climate change on the U.S. agricultural sector with and without considering the effects on livestock yield changes. We then examine how big the difference will be if we include livestock implications into the analysis.

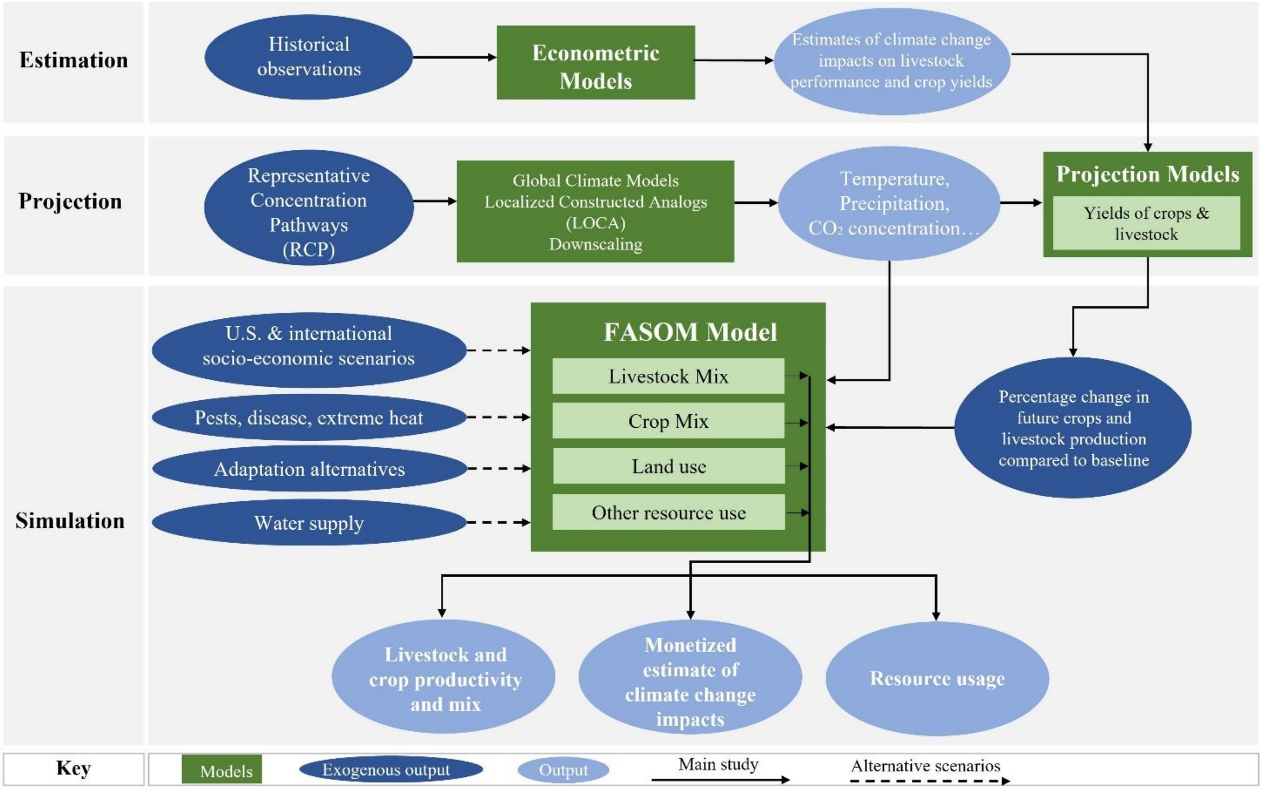

Figure 2: Climate change impacts on U.S. livestock sector modelling approach

3.1 Estimation

Numerous studies have estimated climate change impacts on agricultural production (Adams et al. 1990; Klein et al. 2014). To do that either crop simulation (Fei et al. 2017) or econometric models (Mérel and Gammans 2021) are commonly used when studying crop yield consequences. Since we do not have access to applicable simulation models for livestock, we will pursue econometrics based estimations using panel state level data with the finest time scale available. We will take results from fixed effects panel econometrics model estimations for the climate change impacts on hog and chicken performance, including hog slaughter weight, piglet litter size, piglet survival rate, broiler slaughter weight, rate of lay, and broiler survival rate obtained by Cheng (2022). For other livestock species, we will use estimation results from existing studies. Specifically, feedlot beef production by Yu (2014), milk production by Fan (2018), cattle calving rates and calf death loss by Wang (2020). In these estimations, temperature, relative humidity, temperature and humidity index (THI) (Ekine-Dzivenu et al. 2020) are considered the key explanatory variables as the heat stress is the major threat to livestock performance.

3.2 Projections

To project climate implications on livestock performance, we evaluate the estimated impacts from previous stage over climate scenarios. We will use scenarios from the from the Climate Model Intercomparison Project 6 (CMIP6) collection of results from General Circulation Models (GCMs) that reflect alternative future emission Representative Concentration Pathways (RCPs) scenarios. RCPs are prescribed pathways for greenhouse gas and aerosol concentration trajectory used to describe different climate futures (Intergovernmental Panel on Climate Change 2014) and in this study we consider RCP4.5, the most probable baseline scenario which results in about 1.8 °C temperature change by 2100 and RCP 8.5, the worst climate change scenario projected which predicts an increase of 3.7 °C in temperature (Pachauri et al. 2014). Climate projections out to 2100 were obtained for six GCMs: CanESM2, CCSM4, GFDL-CM3, GISS-E2-R, HadGEM2-ES, and MIROC5. The temperature, relative humidity and precipitation outputs from those GCMs were statistically downscaled for the continental United States (CONUS) using the Localized Constructed Analogs (LOCA) approach (Pierce, Cayan and Thrasher 2014). We will evaluate the climate change impacts to derive future percentage change estimates of the consequent effects on livestock yields.

3.3 Simulation

The agricultural component of the Forestry and Agricultural Sector Optimization Model (FASOM) is employed to simulate climate change implications on agricultural sector including and excluding livestock implications. FASOM is a dynamic, nonlinear and price endogenous programming model for the forest and agricultural sectors in the United States. Economically FASOM simulates a perfectly competitive agricultural market in equilibrium by maximizing the total social welfare subject to resource constraints (Adams et al. 2005). The objective of this model is to maximize the integral of the area under commodity specific demand curves less that under import supply and factor supply curves as discussed in McCarl and Spreen (1980). When solved it yields a simulation of a perfectly competitive land allocation among crops, grasslands and livestock plus results on crop and livestock mix, total production, processing activity, bioenergy production, exports, domestic consumption and commodity prices (Fei et al. 2017).

In this study, we embedded the projected percentage change of livestock production as exogenous shocks into FASOM following Fei, McCarl, Thayer (2017) and Fei et al. (2021). The projection results will be discussed in section 3.5. Livestock feed usage is then adjusted by livestock finishing weight changes. And climate change projections for crops based on recent efforts (Fei et al. 2021) is also integrated into the model. Running the sector model with and without including livestock sensitivity yields results on what considerations on livestock does in terms of altering impacts on crop and livestock production, animal feeding, land allocation, commodity consumption, exports, imports, market prices and welfare.

3.4 Scenario setup

A set of comparison scenarios with and without the impact of climate change on livestock based on Fei et al. (2021) will also be made to investigate the indirect impact of climate change on the livestock sector. To be more specific, we include the following three scenario setups:

Baseline: The baseline scenario is used to describe a current situation where no climate change or other additional settings are included. Results from other scenarios will be compared with the baseline in order to obtain the response of different settings. Here we use 2019 as the baseline year (referred to as "2020" since FASOM operates on a 5-year time step), which at the time of the analysis was the most recent year for which full data on yield, land allocations, total production, and commodity prices were available from USDA Annual Agricultural Statistics. Following Fei et al. (2021), projections for population, demand, GDP and international trade will also be included.

<u>Climate change scenario with the inclusion of livestock sector</u>: This scenario will be referred to as "general climate change scenario" in the following discussions. Based on the baseline scenario, we incorporate the projected climate change impacts under 12 alternative cases (combination of 6 GCMs and 2 RCPs) up till the end of this century. For the convenience of discussion, we will present our results using "degree arrival" instead of GCM and RCP combinations to describe the level of climate change. For example, 3 °C arrival refers to the case where global average temperature increases by 3 °C since 1900. Higher degree arrival indicates worse climate change situation.

<u>Climate change scenario without the inclusion of livestock sector</u>: In this setup we keep most of the settings in general climate change scenario, except that we do not include livestock sensitivity yields. By comparing the results from this scenario to the general climate change scenario, we could obtain the overall climate change impacts on livestock sector.

3.5 Projected percentage change in production

The percentage changes of livestock production obtained from the projection process are included in the simulation model as exogenous input. We consider production changes for a large variety of livestock, including beef cow, dairy cow, hogs for slaughter, feeder pigs, cull sows, slaughter lambs, ewes, broilers, turkeys and etc. Using 2020 as baseline year, projections for livestock products from these animals are obtained for different GCM and RCP scenarios as described in methodology section, ranging from 2021 to the end of this century. And in the projection we use 21 years rolling window estimation to reduce the fluctuation and outliers caused by GCM projections. Figure 3 presents the percentage change in several major types of production comparing averaged 2080 to 2100 projections with baseline, the results are averaged over all GCM and RCP scenarios.

The U.S. poultry industry is the world's largest producer, and the domestic consumption of poultry meat is considerably higher than beef or pork (US Department of Agriculture, Economic Research Service 2022). In 2020, the combined value of production from broilers, eggs, turkeys was $35.5 billion, with most of the production concentrated in southeastern states. By the end of this century, broiler and egg production are projected to be slightly increased (less than 1% in most states) compared to current level. And the magnitude of increase in southern regions would be smaller than the north although the difference is not remarkable.

The change in cattle production varies by region and product types. Fed beef production is projected to decrease by 2% to 3.2% across the entire nation, with the largest decrease in Arizona and New Mexico. Milk production will have a slight decrease in the south and a 1% to 3% increase in the northern area, with the largest gain in the northwest area.

Hog production shows an overall decrease in projection and the southern states will have larger loss compared to northern ones. The largest decrease in hog production is projected to occur in south and east Texas, together with Louisiana and Florida. The production reduction of those traditional major producers of hogs, such as Iowa and Minnesota, is relatively small. One possible explanation is that the climate change impact is smaller in the north, another one is that large operations that specialized in a single phase of production performs better in terms of adapt to the climate challenge.

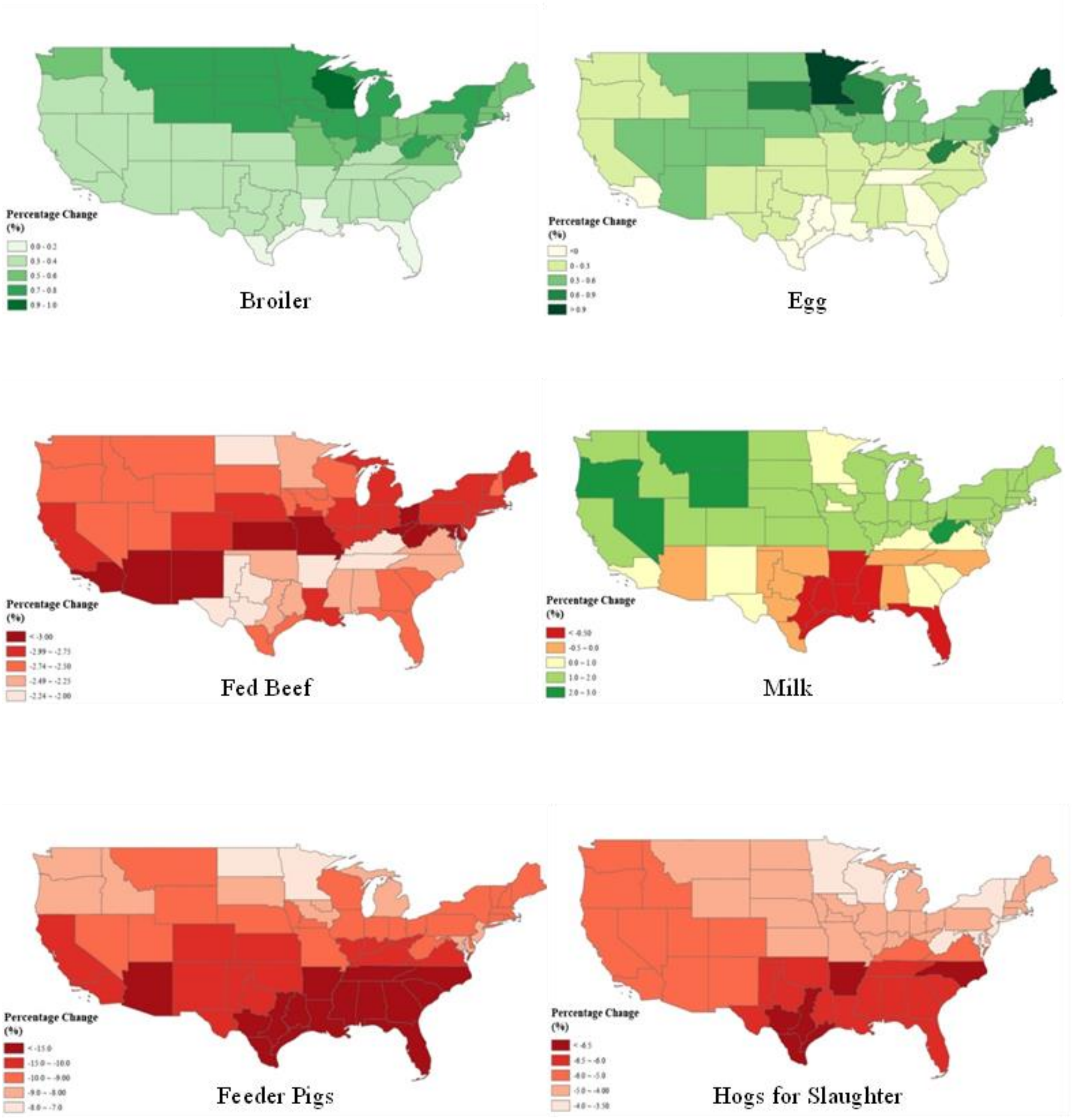

Figure 3: Projected end-of-century yield changes averaged over 6 GCM and 2 RCP scenarios (relative change between 2020 and 2080-2100). Color green indicates a positive change (increase) in production, and color red represents a negative change (decrease), darker color suggests the change is larger in magnitude.

4. Results

In the temperature arrival climate change analysis, several results are compared to the 2020 no-climate-change case. The difference between with and without climate change cases yields the associated impacts of climate change on each category. We will present the effects under each GCM at each degree arrival date for total welfare, as well as price and quantity changes for major commodities.

4.1 Welfare distribution

In Figure 4, we present the changes in welfare distribution averaged across all climate model results at each integer warming level. Specifically, four types of welfare are reported: 1) U.S. domestic consumers, 2) U.S. domestic producers, 3) the sum of welfare for international consumers and producers, 4) the aggregation of the previous three types. Results are shown in billions of 2019 USD.

For the U.S. domestic consumers' welfare, we found a maximum gain of $1.6B at 3 ℃ and a minimum loss of $17.2B at 6 ℃. Given the price and quantity indices, the decrease in consumers' welfare is probably caused by the reduction in livestock production and increased livestock prices. The results for domestic producers' surplus show the opposite sign compared to the consumers' case. The maximum producer surplus is $15.1B at 6 ℃ where consumers' welfare reaches its lowest. For the international consumers and producers, the combined welfare increases up to $5.7B at 5 ℃ and decreases slightly to $5.4B at 6 ℃. The aggregated welfare across all these parties shows an elevating gain from $0.5B at 3 ℃ to $9.8B at 5 ℃, largely because of the producer's surplus gain exceeding consumers' loss. But at 6 ℃ where consumers are facing the most considerable loss, total welfare gain drops to $3.2B.

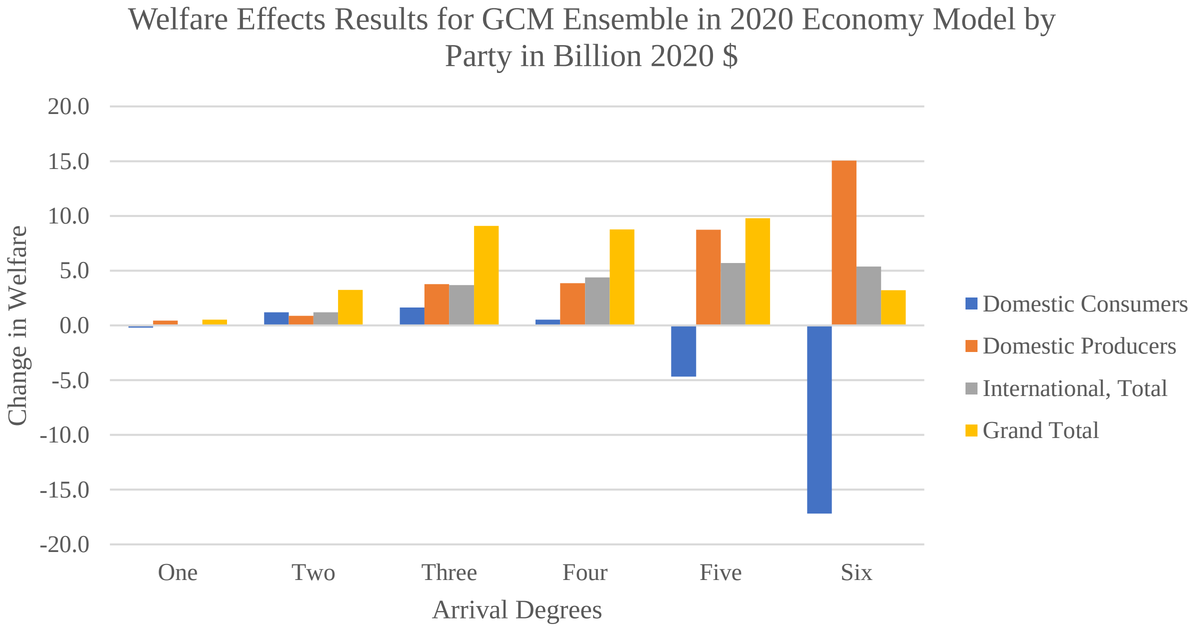

Figure 4: Average annual ensemble welfare distributional effects at different arrival degrees under the 2020 base economy (results in billions of 2020 USD).

4.2 Price and quantity indices

The effects of climate change on average changes in price and quantity for a variety of commodities were computed using Fisher Ideal Index (Figure 5 and Figure 6). For the overall farm production including major crops and livestock products, the price index decreased by 4.7% at 3 ℃ compared to the 2020 levels and then increases over 2020 level by 0.6% at 6 ℃. The quantity index for all farm productions rises by 5.8% at 3 ℃ then drops to 3.4% above the 2020 level.

For crops, we consider cereal and soybean complex, together with cotton and other crops. The largest drop in price indices amongst all crops appears in cotton (with the highest being 48%) at six-degree warming, which is probably driven by the significant increase in cotton production (with the highest being 79%). Price indices for corn and soybeans decrease a little bit while the decreases in price indices for winter wheat and durum wheat are larger, which might be because of the increase in wheat production driven by favor of climate change in the northern area.

For livestock, the price index for all livestock in general first decreases at the three-degree-warming level but then increases and reaches the highest increase of 11% at six-degree. The production indices for major livestock products are decreasing as the warming level gets higher, which indicates the negative impacts of climate change on livestock production. This might be one of the drivers for the increasing price indices. A negative relationship can be found between price and quantity indices, which is consistent with the economic intuition that as price goes up, the demand decreases but supply increases.

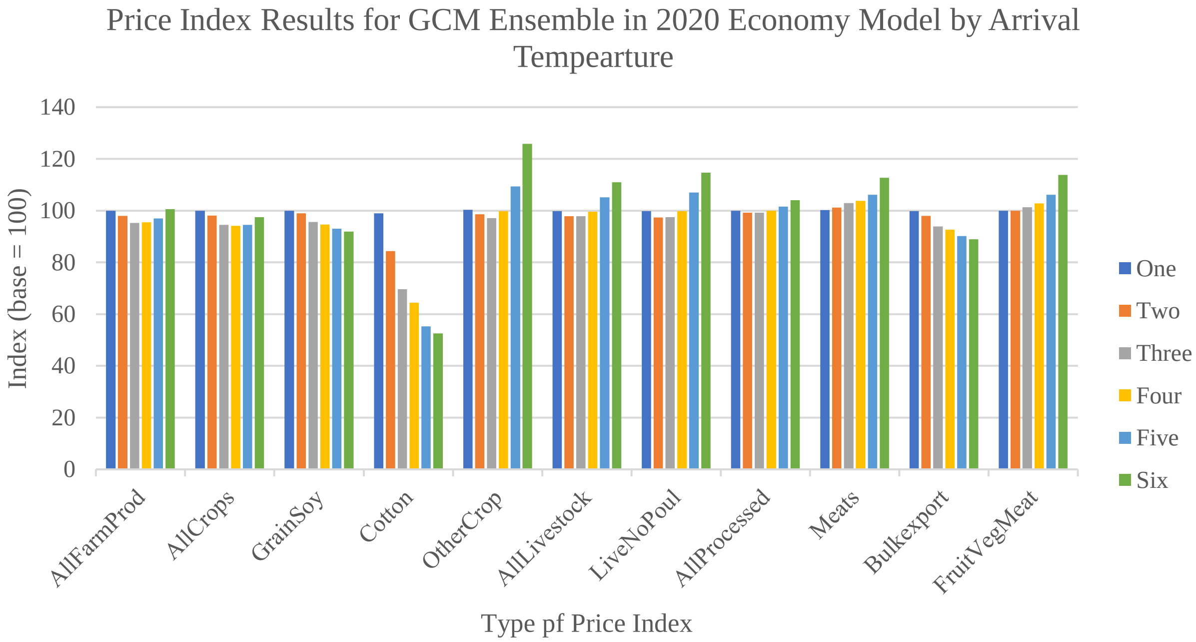

Figure 5: Average annual ensemble price index results at different arrival degrees under the 2020 base economy

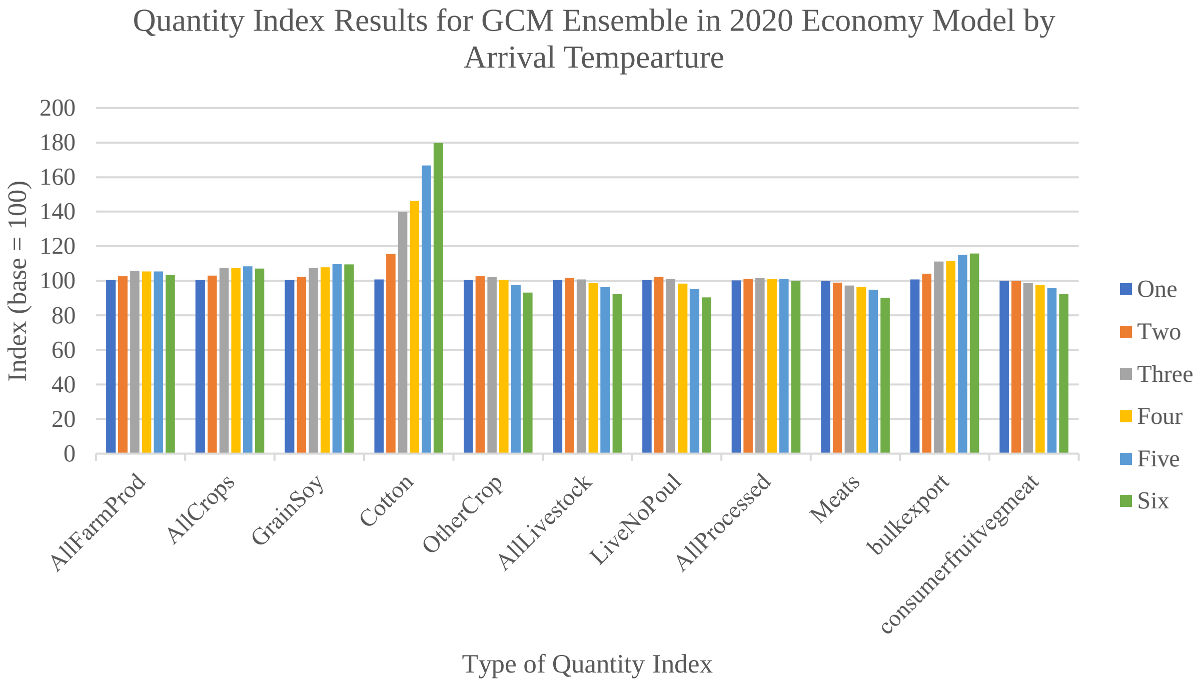

Figure 6: Average annual ensemble quantity index results at different arrival degrees under the 2020 base economy

5. Discussion

Climate change effects on agriculture have been investigated by many researchers, but the aggregate effects of considering climate change influences on the livestock sector has not been addressed. In this study we present new findings regarding climate change impacts on both livestock production and associated welfare and sectoral level resource allocation. We found that climate change impacts on livestock are more influential in the southern area, where livestock production decrease is projected to be larger. As a consequence of decreased production and increasing price of livestock products, consumer surplus will have a significant decrease when climate change arrives at the six-degree-warming level, and producer surplus will change in the opposite direction. The total domestic welfare (consumer surplus loss plus producer surplus gain) loss under the 6 °C warming scenario is $2.1 billion.

The limitation of this research is that it is difficult to accurately predict future economic and market change and the projected results are subject to the settings of future socio-economic conditions. Our model is based on the 2019 economy and this economic condition is assumed to be fixed in analyzing future scenarios. By doing this we could investigate the climate change effects alone. However, in our 100-year time range for the analysis, there are expected to be changes in the economy structure, which may alter the final results. The current counterfactual assumption could be improved by using different baseline year or conducting sensitivity analysis to incorporate more detailed settings for the model components. For future research, the inclusion of other crops and livestock that are relatively minor in production could be a useful extension. The incorporation of these minor species may help explore more adaptation possibilities. Further work could be done to investigate the welfare distribution over different income groups, which may help address the inequality issue caused by climate change.

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