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Climate Change, Heat Stress, and U.S. Dairy Production

Nigel Key, Stacy Sneeringer, and David Marquardt

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Abstract

In the United States, climate change is likely to increase average daily temperatures and the frequency of heat waves, which can reduce meat and milk production in animals. Methods that livestock producers use to mitigate thermal stress—including modifications to animal management or housing—tend to increase production costs and capital expenditures. Dairy cows are particularly sensitive to heat stress, and the dairy sector has been estimated to bear over half of the costs of current heat stress to the livestock industry. In this report, we use operation-level economic data coupled with finely scaled climate data to estimate how the local thermal environment affects U.S. dairies' effectiveness at producing outputs with a given level of inputs. We use this information to estimate the potential decline in milk production in 2030 resulting from climate change-induced heat stress. For four climate model scenarios, the results indicate modest heat stress-related production declines over the next 20 years, with the largest declines occurring in the South.

Keywords: Climate change, dairy, heat stress, productivity, stochastic frontier, technical efficiency

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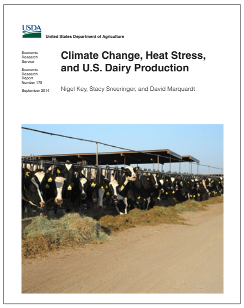

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Climate Change, Heat Stress, and U.S. Dairy Production

Nigel Key, Stacy Sneeringer, and David Marquardt

What Is the Issue?

In many parts of the United States, climate change is likely to result in higher average temperatures, hotter daily maximums, and more frequent heat waves, which could increase heat stress for livestock. Heat stress is characterized by changes in respiration, heart rate, sweating, blood chemistry, and hormones. It can also alter the metabolism of minerals and water and the digestion of nutrients. Animals generally increase their water intake and reduce their feed intake. Depending on the species, heat stress can reduce meat and milk production and lower animal reproduction rates. Livestock producers can mitigate heat stress with shade structures, cooling systems, or altered feed, but these methods increase production and capital costs. Dairy cows are particularly sensitive to heat stress; higher temperatures lower milk output as well as its fat, solids, lactose, and protein content.

The U.S. Global Change Research Program (USGCRP) recognizes that increased heat stress will increase livestock production costs, lower feed efficiency, and compromise livestock health. While the physiological and production responses to heat stress have been widely studied, there have been no attempts to quantify the costs to the U.S. dairy industry of climate change-induced heat stress. In this report, we use operation-level economic data coupled with finely scaled climate data to estimate how the local thermal environment affects U.S. dairies' effectiveness at producing outputs with a given level of inputs. We use this information to estimate the potential decline in milk production in 2030 resulting from climate change-induced heat stress.

What Did the Study Find?

The report found evidence of a significant negative relationship between heat stress and the productivity of U.S. dairies. In 2010, heat stress lowered the value of annual milk production for the average dairy by about $39,000, which equates to $1.2 billion in lost production for the entire dairy sector.

Climate model predictions indicate that, on average, U.S. dairies will experience an annual temperature increase between 1.45 and 2.37 degrees Fahrenheit by 2030. Assuming no adjustments in milk prices, we estimate that the additional heat stress from climate change will in 2030:

- Lower milk production for the average dairy by 0.60 to 1.35 percent, depending on the climate model used;

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- Cause some production loss to almost all dairies, with 4 to 18 percent of dairies experiencing a loss greater than 2 percent;

- Lower total annual production at the State level between 0.05 percent and 4.4 percent, with the greatest losses occurring in Southern States; and

- Lower receipts from total annual milk production at the national level by $79-$199 million, at 2010 prices.

Allowing for higher market prices resulting from the contraction in milk production, we estimate that additional climate change-induced heat stress will in 2030:

- Lower consumer welfare by $64-$162 million because of higher milk prices, and

- Lower producer welfare by $42-$108 million because of higher production costs.

Allowing for a continuation of past trends in dairy location and scale of production does not substantially alter the magnitude of the estimated effects of climate-induced heat stress on dairy production. Production effects in the study were mitigated only slightly if dairies moved out of regions forecast to undergo the greatest increases in heat stress, because dairies in these regions contribute relatively little to national output.

While the estimated reductions in output are modest over the next 20 years, losses from heat stress could increase substantially in later decades, depending on the extent of future climate changes. However, there is potential scope for adaptation to future climate change. Because the effects of climate change-induced heat stress will likely increase gradually over time, costs can be mitigated by research and development into heat mitigation technologies and practices. Possible innovations include energy-efficient cooling for animal housing, the adoption of heat-tolerant breeds, and improvements in scientific knowledge about the interactions among feed, nutrition, and heat stress.

How Was the Study Conducted?

This report uses operation-level economic data and finely scaled climate data to estimate how the local thermal environment affects the technical efficiency of U.S. dairies. We first estimate the average annual heat load for livestock—the amount of humidity-adjusted heat that animals are exposed to—in different regions using 16 years (1990-2005) of daily weather data. We match this climate information with farm production data drawn from the Agricultural Resource Management Surveys of U.S. dairies conducted jointly by USDA's Economic Research Service and National Agricultural Statistics Service in 2005 and 2010. We then estimate the relationship between the average annual heat load and dairy productivity using an econometric production model. Results from this model provide information about how much milk output would decline if there were an increase in the heat load.

Next, we use forecasts from four global climate models to provide a range of predicted heat loads in different regions in 2030. Using these climate forecasts and estimates from the econometric production model, we forecast the potential milk production losses associated with climate change. We explore how the magnitude of the production effects varies across States. We also explore how these effects would differ if geographical growth patterns in milk output were to follow historical trends, or if production were to shift from States experiencing relatively large increases in temperature to States experiencing smaller increases.

Climate Change, Heat Stress, and Dairy Production

Introduction

Global climate change is expected to alter the temperature, precipitation, water availability, and carbon dioxide levels in the atmosphere in ways that will affect the productivity of crop and livestock systems (Hatfield et al., 2008). For livestock, climate change could affect the costs and returns of production by altering (1) the price and availability of feed crops, (2) the location and productivity of pasture and rangeland, (3) the distribution of livestock parasites and pathogens, and (4) the thermal environment of animals—thereby affecting animal health, reproduction, and the efficiency with which livestock convert feed into retained products (especially meat and milk). This report evaluates the potential economic implications of climate change acting through this fourth mechanism, focusing on U.S. dairies – the livestock sector most affected by heat stress.

In many parts of the United States, climate change is likely to result in higher average temperatures, hotter daily maximums, and more frequent heat waves – all of which could increase thermal stress for livestock. Thermal stress reduces meat and milk production and lowers animal reproduction rates. Methods that livestock producers use to mitigate thermal stress – including modifications to animal management or housing – tend to increase production costs. According to the most recent assessment report by the U.S. Global Change Research Program: "The projected increases in air temperatures will negatively affect confined animal operations (dairy, beef, and swine) located in the central United States, increasing production costs as a result of reductions in performance associated with lower feed intake and increased requirements for energy to maintain healthy livestock" (USGCRP, 2009). Despite such forecasts, no studies have estimated these potential heat stress-related costs at the national level.

This report provides estimates of the relationship between the thermal environment and the productivity of U.S. dairies in order to provide information about the potential implications of climate change-induced heat stress for the livestock industry. The analysis focuses on dairies because dairy cows are particularly sensitive to heat stress, and the dairy sector has been estimated to bear 53 to 64 percent of the costs of heat stress to the livestock industry (St-Pierre et al., 2003).

First, we estimate the current average heat load for livestock throughout the United States using historical daily weather data. We match this climate information with farm production data drawn from nationally representative surveys of U.S. dairies conducted in 2005 and 2010. We then estimate the relationship between the current average heat load and dairy productivity using an econometric production model. Results from this model provide cross-sectional information about how much milk output declines as heat loads increase.

Next, we use forecasts from four global climate models to provide a range of predicted heat loads in different U.S. regions in 2030. Using these climate forecasts and estimates from the econometric production model, we forecast the potential milk production losses associated with climate change. We explore how the magnitude of the production effects varies across States. We also explore how these effects would differ if regional growth patterns in milk output were to follow historical trends or if production were to shift from regions experiencing relatively large increases in temperature to regions experiencing smaller increases.

Results of the econometric production model indicate a robust statistically significant negative relationship between average heat stress and milk output. Depending on the climate model used, the results imply that the additional heat stress caused by global warming could reduce milk production for the average U.S. dairy by about 0.60 to 1.35 percent per year in 2030, with larger declines predicted for dairies in the South. The total U.S. annual welfare costs of climate change-induced heat stress in dairies range between an estimated $106 million and $269 million. These results assume producers have a limited ability to respond to climate change through adoption of new technologies, genetic improvements, or relocation to cooler regions. Consequently, these estimates can be considered an upper bound on the effects of climate change-induced heat stress.

While the estimated reductions in dairy output are relatively modest over the next 20 years, temperature increases are predicted to be larger in subsequent years, which could result in substantially larger losses from heat stress. In addition, this report considers the potential costs of heat stress only and not climate-related costs resulting from higher prices for feed crops, reduced productivity of pasture and rangeland, or the increased prevalence of livestock parasites and pathogens.

Heat Stress and Dairy Productivity

Depending on environmental conditions (humidity, wind speed, radiation, etc.), every animal has a thermoneutral zone—an optimal range of temperatures in which it can maintain a normal body temperature without altering its behavior or physiological functions. Above these temperatures, an animal may experience changes in respiration rate, heart rate, sweating, blood chemistry, and hormones (Fuquay, 1981; Kadzere et al., 2002; St-Pierre et al., 2003). Heat stress can also affect the animals' metabolism of minerals and water as well as nutrient digestibility. Behaviorally, animals under heat stress generally increase their water intake and reduce their feed intake. Depending on the species, the thermoregulatory responses to heat stress can reduce livestock productivity.

Because of the high metabolic heat production associated with rumen fermentation and lactation, dairy cattle are particularly sensitive to heat stress. In dairy cows, higher temperatures lower milk output and reduce the percentages of fat, solids, lactose, and protein in milk (Kadzere et al., 2002; St-Pierre et al., 2003; West, 2003). Heat stress also reduces the fertility of cattle and dairy cows, reducing reproduction rates.

Heat Stress and Other Livestock Species

While some breeds of ***beef cattle*** are less susceptible to heat stress than common dairy cow breeds, beef cattle generally have similar physiological responses to heat stress. In beef cattle, heat stress has been observed to decrease dry matter intake and reduce the rate of weight gain (Lippke, 1975; Ray, 1989; Mitlohner et al., 2001).

Swine productivity is also susceptible to warm temperatures and high humidity. Heat stress can lower conception rates and result in fewer viable embryos (Edwards et al., 1968; Wettemann and Bazer, 1984). Sows farrowing during the summer months may have smaller litters and lighter weaning weights than those farrowing during cooler months (Omtvedt et al., 1971.) High temperatures can also lower the feed intake, weight gain, and feed efficiency of swine (Lopez et al., 1991; Nienaber et al., 1989; Collin et al., 2001).

In ***chickens***, heat stress has been shown to lower feed intake and weight gain (Cooper and Washburn, 1998; Yalcin et al., 2001; Quinteiro-Filho et al., 2010; Sohail et al., 2012). Heat stress is also associated with undesirable meat characteristics in broilers (Sandercock et al., 2001; Imik et al., 2012; Zhang et al., 2012). Studies have shown high temperatures lower laying performance, causing decreases in egg weight and shell thickness (Bogin et al., 1996). Extreme heat stress also increases bird mortality rates (Bogin et al., 1996; De Basilio et al., 2001).

Livestock productivity may also decline at temperatures ***below*** the thermoneutral zone, as livestock must expend more energy and increase their voluntary feed intake in order to maintain their core temperature, resulting in lower feed efficiency (NRC, 1981). This can be an important factor influencing the design of housing and in husbandry decisions for cold-susceptible animals such as poultry, swine, and young animals. Dairy cows are relatively cold-tolerant animals, and potential productivity costs associated with low temperatures are not considered in this report.

Mitigating Heat Stress on the Farm

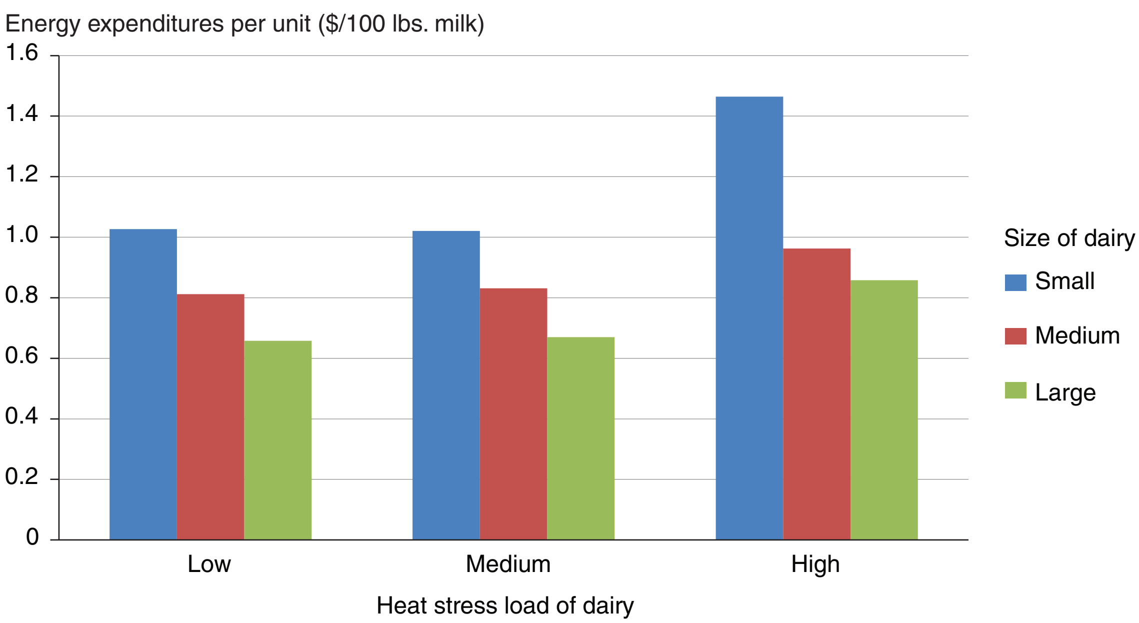
To combat heat stress, farmers can make both longrun and shortrun production decisions. Operators can invest in durable assets (e.g., shade structures and cooling systems) to mitigate the effects of expected heat stress. Operators can also respond, within a particular year, to acute heat spikes by running cooling equipment more or adjusting the quantity/quality of feed rations.

Producers of dairy and beef cattle can mitigate heat stress by providing trees, buildings, or portable structures for shade. For grazing animals, trees surpass buildings in terms of better ventilation, less reflection of solar rays, and natural cooling through evapotranspiration (Brantly, 2013). Shade in combination with cooling (spray and fans) has been shown to offset decreases in milk production and reproductive efficiency resulting from heat stress (Armstrong, 1994). Cows that were cooled with sprinkling and ventilation were found to consume more food and less water and to increase milk, fat, and protein production (Flamenbaum et al., 1995; Her et al., 1998; Igono et al., 1987).

Farmers' efforts to cool cows using ventilation will likely be reflected in energy use. The 2010 Agricultural Resource Management Survey (ARMS) data show that dairies in the warmest regions have higher energy expenditures per unit than those in cooler regions (fig. 1). For example, large dairies spend an average of $0.86 per hundredweight of milk on energy in the warmest regions, compared to only $0.66 in cooler regions.

Altering feed rations can also reduce the effect of heat stress on dairy and beef cattle. Heat stress substantially increases the energy required for physiological maintenance, reducing the energy available for meat or milk production. At the same time, heat stress induces cattle to reduce their feed

Figure 1
Energy expenditures per unit increase in warmer climates



Notes: The heat stress load for each dairy is based on the Temperature Humidity Index (THI) load (measured in humidity-adjusted degree hours) corresponding to the location of the dairy: Low (THI load<4,000); Medium (4,000 ≤ THI load < 12,000); High (12,000 ≤ THI load). Dairy size is based on milk production: Small (milk < 1,500,000 lbs.); Medium (1,500,000 ≤milk <5,000,000 lbs.); Large (5,000,000 lbs. ≤ milk).
Source: 2010 USDA Agricultural Resource Management Survey, Dairy Cost and Returns Report.

intake. To compensate for these changes, dietary recommendations include increasing the nutritional quality of forages, lowering fiber content, and increasing fat levels and digestibility of feed (West, 1997). Other recommendations include altering feeding times to coincide with the cooler times of the day and reducing the effort required by animals to access food, minerals, and water.

A possible adaptive response to a warming climate is to select cross dairy breeds to take advantage of the relative vigor of first-generation crosses (McDowell et al., 1996). Another option is to switch to breeds of cattle that are better suited to high temperatures. For example, Sharma et al. (1983) found that Jerseys were more resistant to heat stress in terms of milk production than Holsteins. The 2010 ARMS data show that Jersey cows were more common on dairies located in warmer regions (fig. 2). For all three dairy size categories, dairies in the highest heat load regions have the greatest share of Jersey cows in their herds, suggesting breed selection is being used to cope with heat stress.

Benefits and Costs of Mitigating Heat Stress

Producers can mitigate the negative effects of heat stress (lower revenue from less output) by increasing the quantity or quality of feed, using more electricity for cooling, or updating cooling equipment. Because these options are costly, producers must weigh the additional revenues that can be earned from heat stress mitigation against the mitigation costs. This tradeoff can be illustrated graphically (fig. 3). The upper solid curve in the figure shows the total revenue earned for different levels of the heat stress

Heat Stress Mitigation and Other Livestock Species

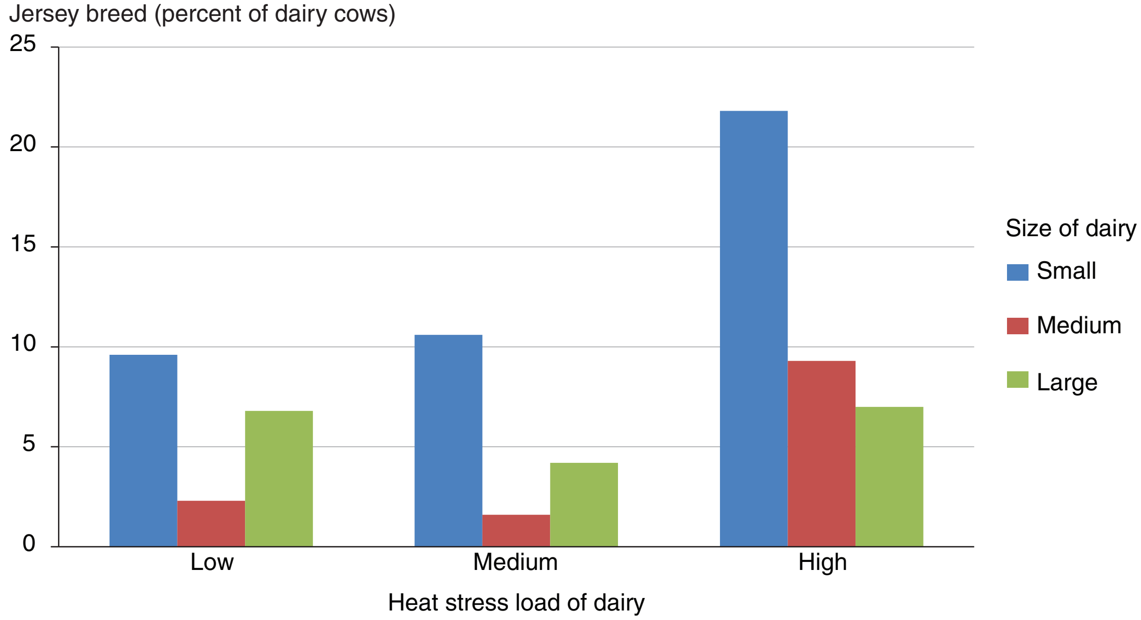
Heat mitigation strategies for ***hogs and pigs*** often emphasize barn design and ventilation, since most U.S. swine are raised indoors. Ventilation can be combined with intermittent sprinkler systems that wet the animal and allow the moisture to evaporate (Hahn, 1985). Evaporative cooling units use the heat from the air to vaporize water, which cools the surrounding air as it evaporates. Other options include air conditioning units, fresh air vents, additional insulation near roofs, and larger attic spaces for better ventilation (Guthrie, 2011).

Other strategies to mitigate heat stress in swine include reducing the stocking density in barns. Animals generate heat through their metabolism, so lowering the density can reduce the amount of heat generated in the barn. In addition, high-density stocking may not allow pigs to extend their frames to maximize heat loss or permit sufficient ventilation around their bodies.

As with swine, most ***chickens and turkeys*** in the United States are raised in buildings, so strategies to reduce heat stress are similar. Housing should be designed to promote good ventilation and air movement. Houses with tunnel ventilation or ventilation fans, sprinklers, or evaporative cooling are recommended in hot regions (University of Kentucky, 2013). Stocking density in houses should be limited so as to not exceed the capacity of the ventilation system. High density adds more metabolic heat to the house, increases radiant heat transfer from bird to bird, and traps more hot air between birds.

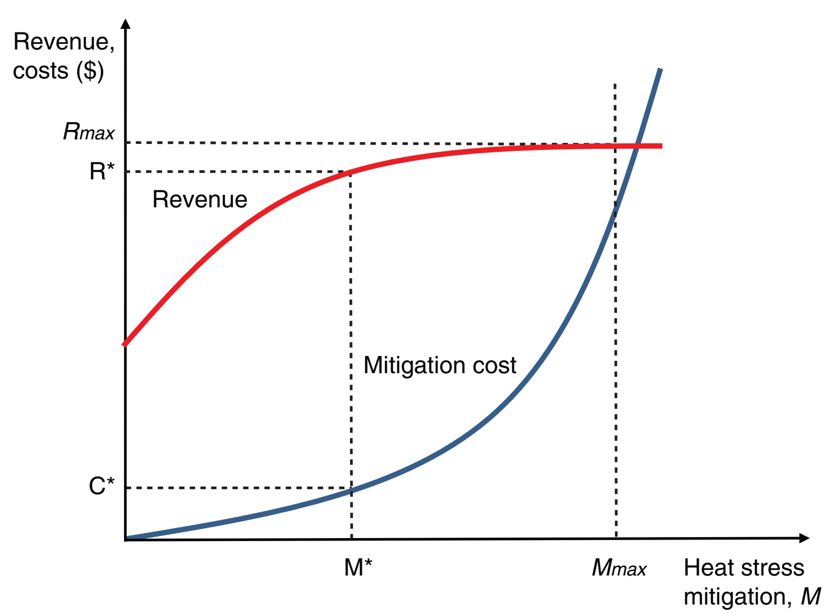
Other heat stress mitigation practices in poultry include nutritional supplements for feed or water to maintain the electrolyte balance of the birds. Dietary adjustments include offering feed with higher nutrient concentrations and increased energy content. Since heat is generated during digestion, another approach is to withdraw feed prior to peak daily temperatures (Butcher and Miles, 2013).

Figure 2
Share of Jersey breed in herd increases in warmer climates



Notes: The heat stress load for each dairy is based on the Temperature Humidity Index (THI) load (measured in humidity-adjusted degree hours) corresponding to the location of the dairy: Low (THI load<4,000); Medium (4,000 ≤ THI load < 12,000); High (12,000 ≤ THI load). Dairy size is based on milk production: Small (milk<1,500,000 lbs.); Medium (1,500,000 ≤ milk < 5,000,000 lbs.); Large (5,000,000 lbs. ≤ milk).
Source: 2010 USDA Agricultural Resource Management Survey, Dairy Cost and Returns Report.

Figure 3
Optimal heat stress mitigation



Note: The upper solid line shows the revenue earned from livestock as a function of the amount of heat stress mitigation. Increasing mitigation above Mmax, does not result in further increase yields or revenue – no longer experience productivity losses from heat. Optimal heat stress mitigation is M*, because below this level the additional revenue from increasing mitigation outweighs the additional cost of the mitigation, and above this level the costs of additional mitigation outweigh the additional benefits.
Source: USDA, Economic Research Service.

mitigation. As mitigation increases, revenues from the sale of livestock products increase until they reach R_{max}. Increasing mitigation efforts above M_{max}, does not further increase yields or revenues—animals no longer experience productivity losses from heat beyond this point.

The bottom solid curve in the figure shows the total costs of heat stress mitigation. In this example, mitigation costs grow at an increasing rate. Net revenues are the distance between the revenue line and the mitigation cost line. The optimal level of heat stress mitigation M^* is the point where net revenues are maximized—where the distance between the lines is greatest. Below M^*, the additional revenues from increasing mitigation outweigh the additional costs of mitigation, and above M^*, the costs of additional mitigation outweigh the additional benefits. Hence, it is not economically optimal to mitigate all heat stress because the costs of doing so would outweigh the benefits.

Cost Estimates of Heat Stress in Livestock Highest for Dairy

Heat stress will impose different costs on different livestock sectors, depending on the species resistance to heat stress, the costs of mitigating heat, and the location of production. St-Pierre, Cobanov, and Schnitkey (2003) estimated the costs of heat stress for several livestock categories (table 1). The authors compared animal performance, reproduction, and mortality in the current (2002) climate to a hypothetical "ideal" climate in which livestock are always in their thermoneutral zone. They define the cost of heat stress as the gross value of lost production plus expenditures on heat mitigation. Using a model that relies on experimental data linking livestock productivity to heat stress, assumptions about producers' heat mitigation expenditures, and prices of outputs, St-Pierre, Cobanov, and

Table 1
Total costs of heat stress—no climate change

	Total annual U.S. economic losses (mil. $/yr)		Percent of total	
Livestock category	Optimum heat mitigation	No mitigation	Optimum heat mitigation	No mitigation
Dairy (total)	896.7	1,506.7	53.0	63.9
Cows	848.4	1,458.4	50.1	61.9
Heifers (0-2 years)	12.1	12.1	0.7	0.5
Heifers (1-2 years)	36.2	36.2	2.1	1.5
Beef (total)	370.1	370.1	21.9	15.7
Cows	87.7	87.7	5.2	3.7
Finishing cattle	282.4	282.4	16.7	12.0
Swine (total)	299.2	315.6	17.7	13.4
Sows	97.1	113.0	5.7	4.8
Growing to finish	202.1	202.6	11.9	8.6
Poultry (total)	127.3	164.6	7.5	7.0
Broilers	51.8	51.8	3.1	2.2
Layers	61.4	98.1	3.6	4.2
Turkey	14.1	14.7	0.8	0.6
All Livestock	1,693.3	2,357.0	100.0	100.0

Source: St-Pierre, Cobanov, and Schnitkey (2003).

Schnitkey estimated that for all major U.S. livestock industries, heat stress imposes annual costs between $1.69 billion and $2.36 billion (in 2002 dollars).

The dairy sector exhibited the largest losses from heat stress (53.0-63.9 percent of total losses, depending on level of mitigation). Dairy cows are particularly sensitive to heat stress because of the heat generated by milk production and rumen fermentation (Kadzere et al., 2002). Lactation in high-yielding milk cows requires large quantities of feed. The process of metabolizing nutrients generates heat, which must be dissipated in a warm climate to maintain normal physiological functioning. The remaining shares of livestock losses from heat stress are in the beef (15.7-21.9 percent), swine (13.3-17.7 percent), and poultry (7.0-7.5 percent) sectors.

Climate Change and Heat Stress

Measuring Heat Loads

Understanding how heat stress varies across the country and how it might change in the future requires a method for relating climatic characteristics (i.e., temperature and humidity) to heat stress. An upper critical temperature can be used to define when an animal reaches the limit of its thermoneutral zone and begins to exhibit heat stress. For example, the upper critical temperature for dairy cattle is usually given as 25-26 °C (77-79) (Berman et al., 1985). However, other environmental factors—particularly humidity—will affect the temperature at which an animal experiences heat stress. The temperature humidity index (THI), a combined measure of ambient temperature and relative humidity, has been shown to better quantify thermal stress on livestock than temperature alone (Ravagnolo et al., 2000). The THI is calculated as:

(1) $$THI = (\text{dry bulb temperature } {}^\circ C) + (0.36 \times \text{dew point temperature } {}^\circ C) + 41.2.$$

The upper critical THI above which animals suffer from heat stress varies by species and age. This THI threshold has been estimated to be about 70 humidity-adjusted degrees for lactating dairy cows, 72 degrees for growing-finishing hogs, 75 degrees for beef cows, and 78 degrees for broiler chickens (St-Pierre et al., 2003).

The THI *load* provides a measure of the amount of heat stress an animal is under (St-Pierre et al., 2003). The THI load (measured in humidity-adjusted degree hours or days) increases with the duration and extent that an animal in a particular location is above its critical THI threshold. The annual THI load is roughly analogous to "cooling degree days," a concept often used to convey the amount of energy needed to cool a building in the summer.[1]

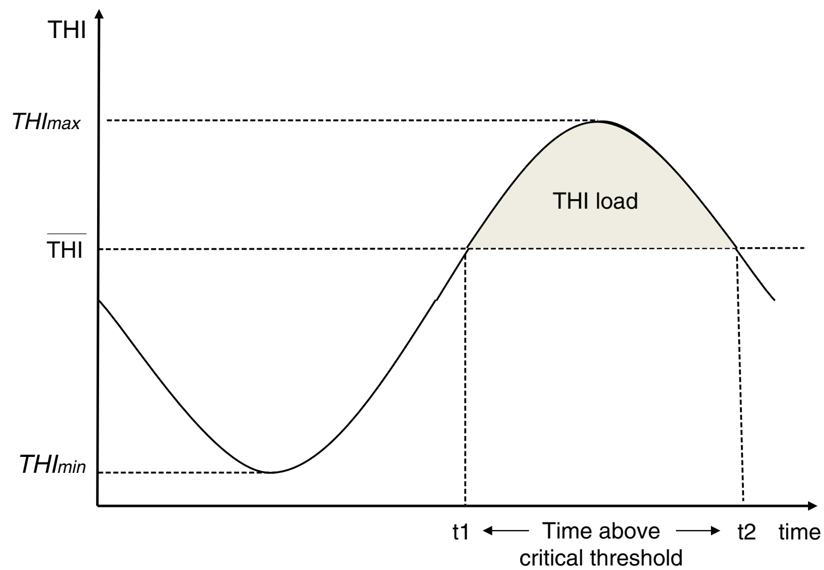
Calculation of the THI load for 1 day can be illustrated graphically (fig. 4). The solid sinusoidal line represents the THI as it fluctuates over 24 hours. The critical THI threshold is indicated by the horizontal line $\overline{THI}$. The THI load is shown as the shaded area in the figure. The THI load can increase with higher temperatures or higher humidity, with more time spent above the threshold, or with a lower critical THI threshold (implying the animal is more sensitive to heat). Given a species-specific THI threshold value, and assuming the THI is a sinusoidal function and that the minimum temperature can be used to approximate the dew point, it is possible to estimate the daily THI load using only the minimum and maximum temperatures (see Key and Sneeringer, 2014, for more details about calculating the THI load using weather data).

The THI load is generally highest in the South and in the summer months (fig. 5).[2] In the vast majority of the country, dairy cows experienced no heat stress (they were below their THI threshold) from November through April. In all but the most mountainous regions, dairy cows experienced some heat stress during July and August.

[1]Cooling degree days measure how much and for how long air temperature is higher than a specific base temperature. Cooling degree days do not account for humidity. The formula used to calculate cooling degree days typically does not account for the daily sinusoidal temperature pattern.

[2]The spatial unit in these maps is a 4km-squared land area (grid cell). The maps are generated using monthly data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM, described in the next section).

Figure 4
Temperature Humidity Index load for one day



Source: USDA, Economic Research Service.

Current Climate and THI Loads

To establish a baseline level of heat stress for different regions of the country, we calculate the annual THI load using daily weather data from 1990 to 2005 and 2010 compiled by Schlenker and Roberts (2009).[3] Schlenker and Roberts estimate daily minimum and maximum temperatures using daily weather station records combined with monthly PRISM grid cell weather data. The PRISM data are generated by interpolating between weather stations to generate weather variable estimates for each 4km grid cell in the United States.[4] We use the daily weather data from 1990 to 2005 to calculate the THI load for each day and then add the daily THI loads in each year to derive the annual THI load. Variations in the weather from year to year could cause the THI load in any one year to differ from the average or expected weather—that is, the climate. Consequently, to characterize the climate for each 4km cell, we average the 1990-2005 annual THI loads to derive the average annual THI load.

Figure 6 illustrates the range of average annual THI loads in the contiguous 48 States for dairy cows, hogs, and poultry (using critical THI thresholds of 70, 72, and 78 humidity-adjusted degrees, respectively). Not surprisingly, the THI load is greatest in the South and lowest in the North and the mountainous regions. To illustrate where livestock production is located relative to the THI load, the map also displays the geographic distribution of animals.

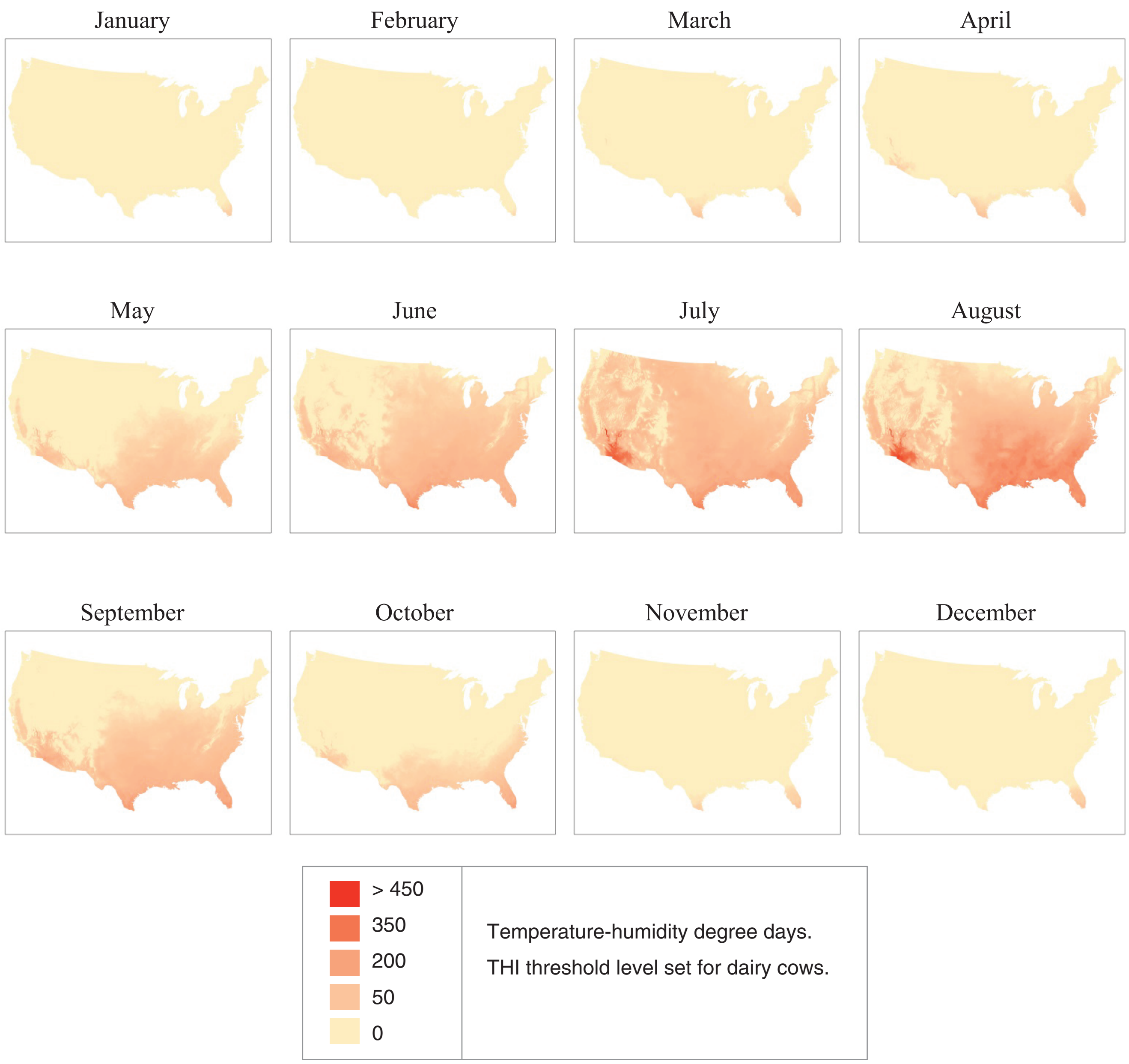
The top map shows concentrations of dairy cows in California's Central Valley, Idaho, Wisconsin, New York, and Pennsylvania. Few dairies are located in the very warm Gulf Coast region (which

[3]We use 16 years of weather data rather than the 30-year averages normally used in climate studies because we believe the average weather in the most recent 16 years (1990-2005) better characterizes the 2005 climate than does the average weather over the previous 30 years (1975-2005).

[4]For more information on PRISM, see http://www.prism.oregonstate.edu/.

Figure 5

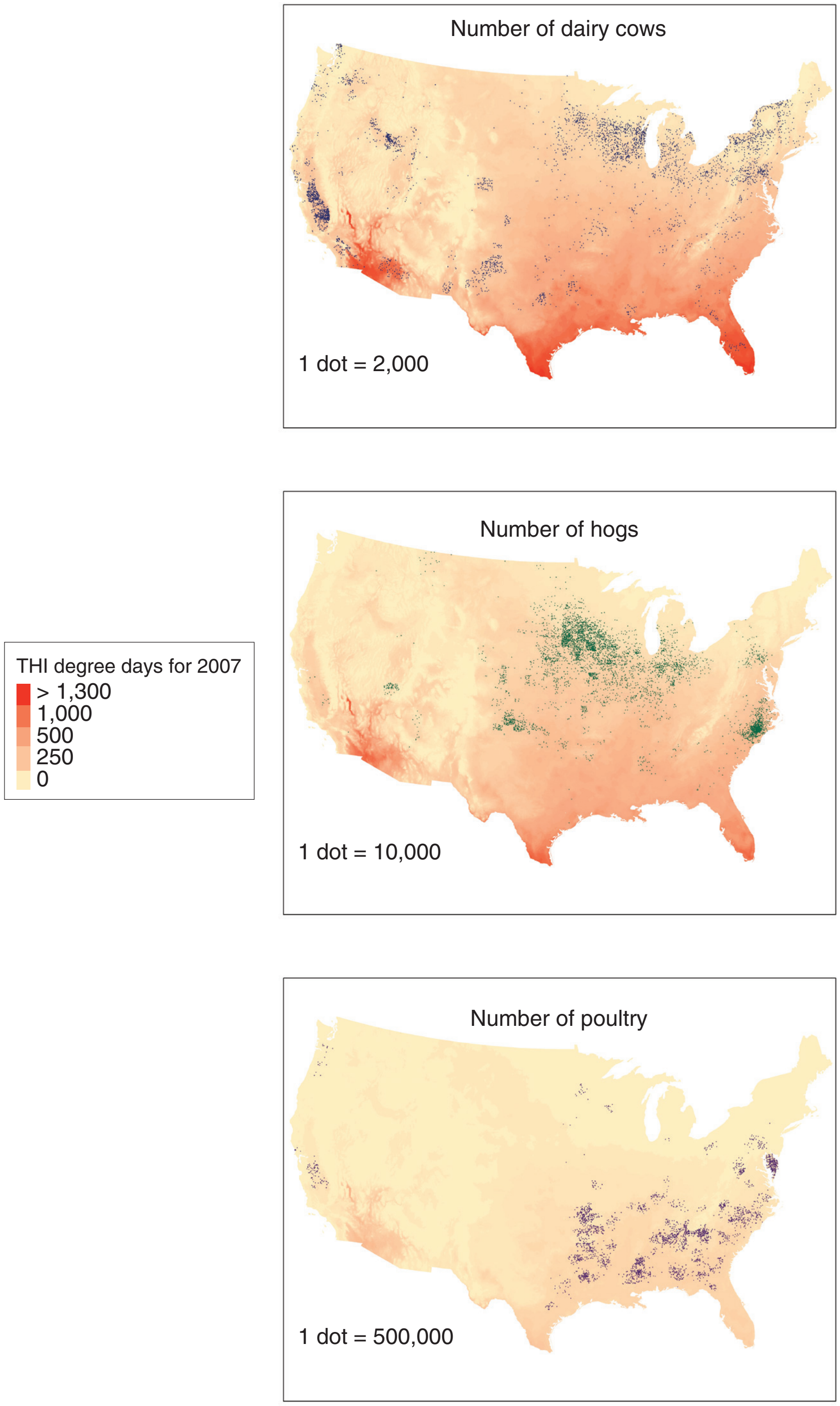
Temperature-Humidity Index load for dairy cows by month, 2007



Source: USDA Economic Research Service calculations using Parameter-elevation Regressions on Independent Slopes Model data.

Figure 6

Annual Temperature Humidity Index load and location of dairy, hog, and poultry operations, 2007



Source: U.S. Census of Agriculture, 2007 and Parameter-elevation Regressions on Independent Slopes Model data.

includes southern Texas, Louisiana, Mississippi, Alabama, and Florida). A similar pattern emerges for hogs, which have a slightly higher threshold than dairy cows. In contrast, poultry have a much higher THI threshold (bottom map) as shown by lack of regions having more than 1,000 degree days above the threshold (the darker shades on the maps). This may partly explain the greater concentration of poultry production, relative to dairy or hog production, in the Southern States.

In general, livestock production is concentrated in climates that expose animals to less heat stress. This can be seen by comparing the share of animals and the share of land in different heat load categories (fig. 7). For example, in the case of dairies (top chart), most of the "cooler" heat load categories (THI loads between 50 and 400 humidity-adjusted degree days) contain a higher percentage of cows than land.[5] In fact, about 28 percent of all dairy cows are located in the second lowest heat load category (between 50 and 100 humidity-adjusted degree days), compared to about 16 percent of all land. In contrast, most of the "warmer" categories (THI loads greater than 400) contain a lower percentage of cows than land. Hogs and poultry show a similar pattern.

Predicting Future THI Loads

Understanding how climate change will affect THI loads for livestock requires predictions about future temperature and humidity levels in different U.S. regions. For this, we use climate forecasts from four General Circulation Models (GCMs), which estimate patterns of temperature and precipitation based on assumptions about future carbon emissions levels. For this analysis, we use the A1B greenhouse gas (GHG) emission scenario described in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (IPCC, 2007). This "medium" emissions scenario incorporates a variety of midrange assumptions about future population growth, technological change, economic growth, international political cooperation, and the like. While emissions levels in the distant future are highly uncertain, there is relatively little variation between the scenarios before 2050 (Jones et al., 2009). Since our analysis focuses on 2030, it is unlikely that an alternative GHG emissions scenario would substantially change the outcomes.

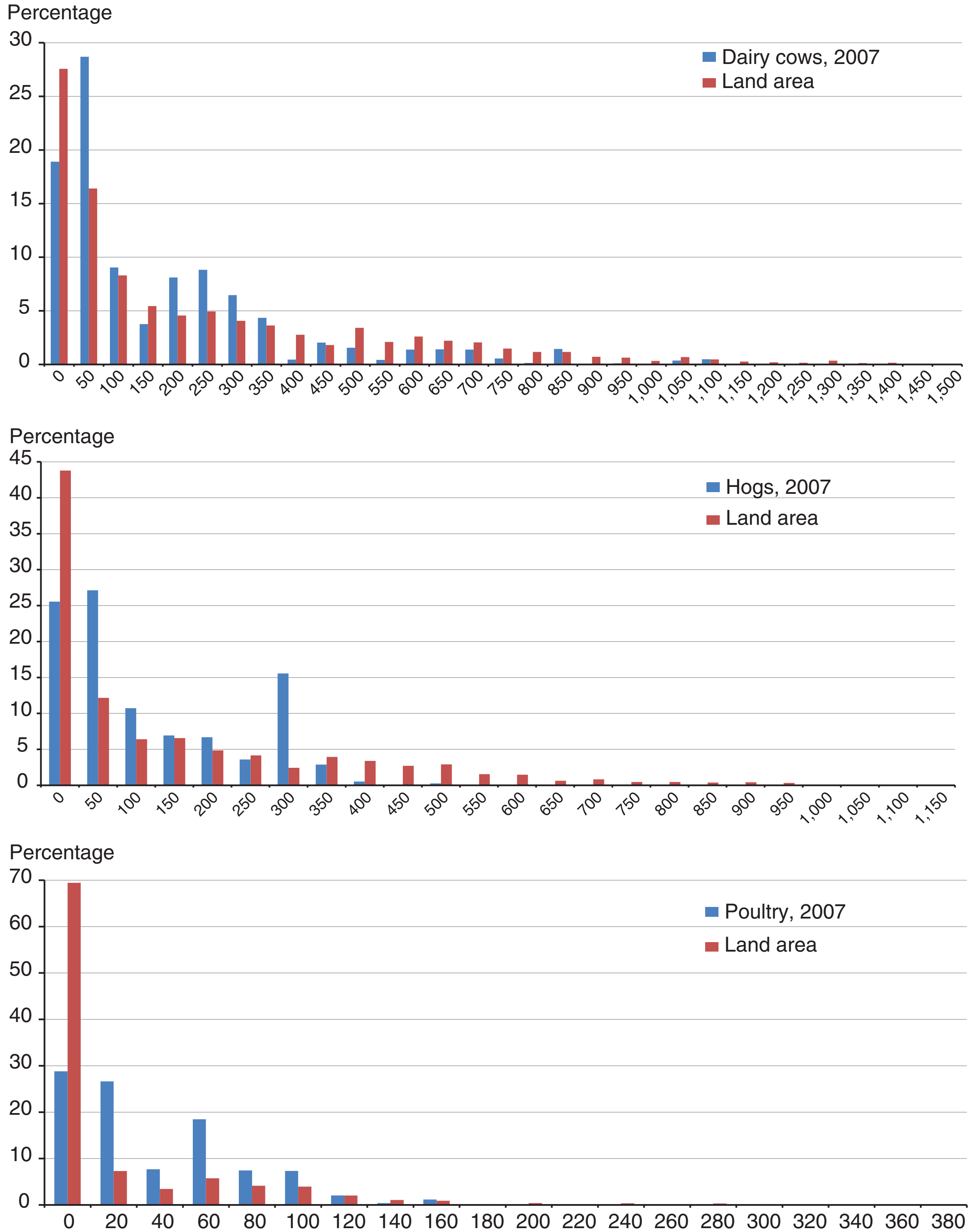
The GCMs used in this study are listed in table 2. GCMs model the atmosphere in stacks of cells at a course spatial and temporal resolution. Because of this, the three-dimensional GCM output usually must be "downscaled" to finer-scale two-dimensional data in order to study the impacts of climate change on natural systems. The GCM data used in this study were downscaled by Jones, Thornton, and Heinke (2009), who estimated the average monthly precipitation and maximum/minimum temperatures for 2030 based on weather projections for 2021-2040.

To link the downscaled climate model data to specific U.S. regions, we use data from Malcolm et al. (2012), who in turn used the Jones et al. downscaled data to compute the average monthly values for maximum and minimum temperatures on agricultural land within 48 Regional Environment and Agriculture Programming (REAP) regions.[6] We use the predicted monthly temperature data for 2030 at the REAP region level, coupled with baseline estimates of THI load, to calculate the predicted THI load for 2030 (see Appendix for details).

[5]The lowest heat load category (less than 50 humidity-adjusted degree days) is an exception, with a relatively large share of land compared to cows. This is likely because much of the land in this category is in mountainous regions less suitable for agriculture (see fig. 4).

[6]The REAP regions are defined by the intersection of USDA Farm Production Regions (defined by State boundaries) and the USDA Natural Resources Conservation Service's Land Resource Regions (defined by predominant soil type and geography). See Malcolm et al. (2012) for details.

Figure 7
Distribution of animals and land area by annual Temperature-Humidity Index load, 2007



Note: The figures show the share of all animals (dairy cows, hogs, or poultry) and the share of U.S. land in each species-specific THI category. The distributions show that animals are located in cooler regions. Except in the lowest THI load category, which is comprised of mountainous regions, there is generally a higher percentage of livestock than land in low-THI regions. In contrast, most of the higher THI load regions contain larger shares of land than livestock.
For these figures, annual THI load is calculated using monthly PRISM data from 1990 to 2010. County-level measures are then found by averaging across pixels in a county, and across years. Land area in the U.S. and animal inventory in 2007 are displayed according to this averaged measure of THI load in humidity-adjusted days.
Source: Census of Agriculture and Parameter-elevation Regressions on Independent Slopes Model.

Table 2

General circulation models used in study

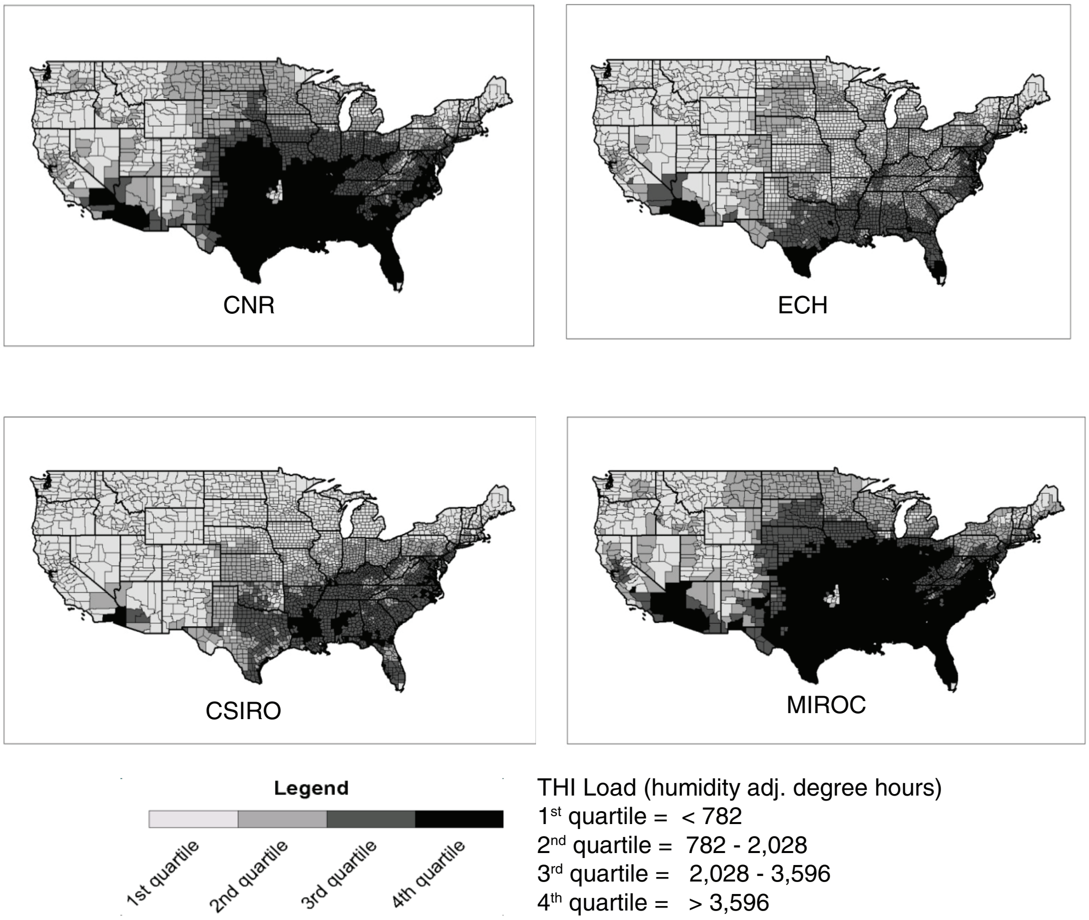
Label	Model name	Institution	Reference
CNR	CNRM-CM3	Centre National de Recherches Meteorologiques (CNRM), Meteo France, France	Déqué et al. (1994)
CSIRO	CSIRO-Mark 3.0	Commonwealth Scientific and Industrial Research Organisation (CSIRO) Atmospheric Research, Australia	Gordon et al. (2002)
ECH	ECHam5 (European Centre, Hamburg)	Max Planck Institute for Meteorology, Germany	Roeckner et al. (2003)
MIROC	MIROC 3.2 (Model for Interdisciplinary Research on Climate)	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	K-1 Developers (2004)

Source: Jones, P., P. Thornton, and J. Heinke (2009).

The predicted change in the THI load for each of the four GCMs varies greatly by region (fig. 8). For all models, the largest increases are forecast in the South. In the CNR and MIROC models, the THI load is expected to increase by over 3,596 degree hours in most of the South.

Figure 8

Predicted changes in dairy Temperature-Humidity Index load between 2010 and 2030, four climate models



Note: See table 2 for explanation of climate model names and sources.
Source: Jones, P., P. Thornton, and J. Heinke (2009).

Estimating the Effect of Heat on Milk Production

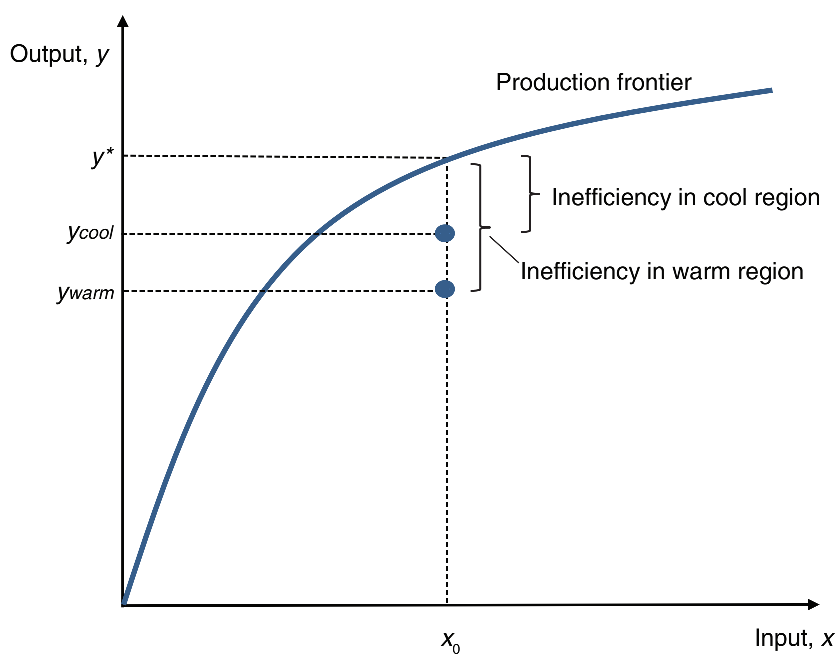
Econometric Model

Estimating how changes in the climate will affect the dairy sector requires information about the relationship between heat (the THI load) and dairy output. To quantify this relationship, we econometrically estimate the relationship between output (milk) and inputs (labor, feed, capital, and other inputs), controlling for characteristics of the dairy operation and operator. Importantly, we allow input productivity to vary according to the THI load—higher THI loads cause lower rates of weight gain and milk production, holding inputs constant. More specifically, we estimate how the THI load affects technical efficiency—how much output is actually produced relative to what could be produced if all inputs were used efficiently.

The concept of technical efficiency and how it changes with the heat load can be explained graphically (fig. 9). The upward sloping curve represents a hypothetical production frontier—the most output y (e.g., milk) that could be produced given a quantity of an input x (e.g., feed) if the input were used efficiently—that is, using the best available production practices in optimal climate. In fact, most operations are not perfectly efficient, so actual production falls below the frontier.

The figure shows two farms located in different climates. Suppose both farms use the same amount of the input x_0 and the farm in a cooler region produces y_{cool}, while the farm in the warmer region produces a smaller amount, y_{warm}. Both farms are inefficient because their output falls below

Figure 9
Temperature Humidity Index load for one day



Source: USDA, Economic Research Service.

the maximum amount that could be produced, y^*. This inefficiency is shown in the figure as the distance between what is produced and the production frontier.

Technical efficiency (*TE*) is a measure of farmers' ability to effectively use the available production technology. It is defined as the ratio of what is actually produced to what could be produced if operating perfectly efficiently. Because more is produced in the cool region compared to the warm region using the same inputs, the farm in the cool region is more technically efficient:

$$TE_{cool} = \frac{y_{cool}}{y^*} > \frac{y_{warm}}{y^*} = TE_{warm} \qquad (2)$$

The essence of our empirical approach is to estimate how technical efficiency responds to a change in the THI load, holding inputs and other factors constant. We do this by econometrically estimating a stochastic production frontier model (see details in the Appendix) that relates inputs to the production frontier while allowing other factors, such as the THI load, to affect efficiency. The model allows us to estimate how a change in the climate (measured with the THI load) would alter a farm's technical efficiency and, consequently, output.

Data

Dairy production data are drawn from the Agricultural Resource Management Survey (ARMS) collected in 2005 and 2010 by USDA's Economic Research Service and National Agricultural Statistics Service. The ARMS targeted dairies in the 24 States with the most dairy production. The surveys collected information on the dairy enterprise: cow inventories, milk production, revenues, technology choices, structures and equipment, input use and expenses, and manure management strategies/technologies. The surveys also elicited information about the whole-farm business, as well as the farm operator and household. Focusing on conventional (non-organic) producers resulted in a sample of 1,123 dairies in 2010 (1,236 in 2005).[7]

Combining ARMS data with supplemental price information, we estimate farm labor, feed, and capital costs.[8] Off-farm wage data from another version of the ARMS are used to estimate the opportunity costs of unpaid labor hours used on the farm. USDA market price data are used to value the reported quantities of homegrown feed and forages fed to dairy cows. ERS researchers also produce annualized estimates of the cost of replacing the capital used for cattle housing, milking facilities, feed storage structures, manure handling/storage structures, feed handling equipment, tractors, trucks, and purchased dairy herd replacements, plus the interest that the remaining capital could have earned in an alternative use.

Milk, which represents about 87 percent of the total value of production for the dairy operations in the sample, is the output in the production function. Inputs include milk cows (average herd size), feed (cost), capital (replacement cost for all buildings and machinery), labor (hours), and other inputs (expenditures on medicine and veterinary services, marketing, custom work, repairs, agricul-

[7]Organic operations are dropped from the samples because they employ a production technology (and face a production frontier) that is distinct from conventional operations and because they contribute a relatively small share to total production.

[8]See MacDonald et al (2007) for more details about the ARMS dairy survey methodology and a description of the sample.

tural chemicals, fuel, and energy). Feed consists of mixes, forage, and grains of varying quality and digestibility, which we aggregate into a single input.

Each dairy in the ARMS is linked to daily, pixel-level climate data using the centroid of the ZIP Code in which the dairy is located. The main variable of interest is the longrun average THI load, which is hypothesized to lower technical efficiency by reducing an animal's output for a given level of inputs. In addition to the longrun THI load, we include a measure of the deviation of the current THI load from the longrun average THI load:

(3) $$THI_t^{Dev} = THI_t - THI_{LR}$$

where THI_t is the THI load in survey year *t* (2005 or 2010) and THI_{LR} is the longrun THI load (the average annual THI load from 1990 to 2005). The deviation from the longrun THI captures the effect of annual THI shocks (heat spikes) on technical efficiency.[9]

Factors beside the THI load that may influence technical efficiency include operator education (college graduate), operator age, operator experience (years producing milk), operation size (total value of production) and a measure of specialization (milk sales as a share of total dairy sales). Summary statistics for the key variables in 2005 and 2010 are given in table 3.

A simple comparison of the characteristics of dairies in different climates suggests an inverse relationship between productivity and THI load (table 4). Larger dairies are over-represented in warmer regions, which results in a positive correlation between size and THI load. To account for this, we compare productivity measures across three levels of THI load using three size categories based on hundredweight of milk produced.[10] Operations in areas with the highest THI loads produce less milk per cow than operations in regions with the lowest THI loads, for all three size categories. Cow mortality rates generally increase with THI load. For medium and large dairy operations (which produce about 85 percent of U.S. milk output), unit costs are higher in the warmest regions compared to the coolest region.

Results of Econometric Model

The stochastic production frontier model consists of two parts: a production frontier (the coefficients indicate the marginal contribution of the inputs to output on the frontier) and inefficiency (the coefficients explain how much the variables cause production to fall below the frontier). In the production frontier equation, the inputs and output are in logarithms, so each coefficient can be interpreted as the percent change in output given a 1-percent change in the input at the sample mean (i.e., the partial output elasticities). All the estimated partial output elasticities—for both 2005 and 2010—are positive (table 5), which is consistent with economic theory.

[9]It is possible that the marginal effect of the THI load increases with the total THI load (i.e., with more extreme heat). We tested this hypothesis by creating a "high THI load" and a "low THI load" variable, defined as the THI load conditional on the THI being above or below 85 humidity-adjusted degrees. We found no evidence to support the hypothesis (Key and Sneeringer, 2014). However, we only observe 2 years of data and may not be able to identify the effect on productivity of very rare extreme heat events.

[10]On average, both the THI load and productivity increase with the scale of the dairy. Hence, we might observe a spurious positive correlation between THI load and productivity if we don't control adequately for operation size.

Table 3

Summary statistics for dairies, 2005 and 2010 samples

Variable	2005 Mean (Std. Dev.)	2010 Mean (Std. Dev.)
Dairy milk production (100 lbs.)	26,196	30,193
	(390,834)	(480,227)
Milk cows (head)	138	148
	(1,895)	(2,099)
Feed (expenditures, dollars)	215,840	304,880
	(3,166,304)	(4,096,994)
Labor (paid and unpaid, hours)	7,239	7,312
	(162,474)	(72,061)
Capital (recovery cost[a], dollars)	79,985	109,495
	(1,199,874)	(1,448,214)
Other inputs[b] (expenditures, dollars)	70,679	91,227
	(966,029)	(1,291,672)
College graduate (1/0)	0.16	0.23
	(2.27)	(2.50)
Operator age (years)	50.92	50.50
	(68.07)	(68.44)
Dairy experience (years)	23.04	26.89
	(75.39)	(73.57)
Dairy share (milk sales/total sales)	0.87	0.87
	(0.45)	(0.36)
Annual THI load (adj. deg. hours)	5,405	6,035
	(20,966)	(27,570)
Average THI load (adj. deg. hours)	4,158	4,661
	(20,305)	(22,673)
Obs.	1,236	1,123

[a] The capital recovery cost is the cost of replacing the machinery and equipment used up in the annual production process, plus the interest that the remaining capital could have earned if invested elsewhere.

[b] Other inputs include veterinary services, medicine, marketing, repairs, custom services, agricultural chemicals, fuel and energy.

Source: 2005 and 2010 USDA Agricultural Resource Management Survey, Dairy Cost and Returns Report.

Table 4
Dairy productivity by THI load and dairy size, 2010

Dairy size	Annual THI load (Adj. Deg. Hours) Low (THI load < 4,000)	Medium (4,000 ≤ THI load < 12,000)	High (12,000 ≤ THI load)
Small (milk < 1,500,000 lbs)			
THI load	2,669	6,696	18,134
Milk per farm (100 lbs.)	7,724	8,037	8,977
Milk per cow (100 lbs./head)	160	161	117
Milk cow mortality rate	0.058	0.059	0.063
Total costs per unit ($/100 lbs.)	37.27	34.35	39.10
Net returns per unit ($/100 lbs.)	-18.43	-15.33	-19.00
Observations	187	197	114
Medium (1,500,000 lbs. ≤ milk < 5,000,000 lbs)			
THI load	2,894	6,324	18,478
Milk per farm (100 lbs.)	24,965	25,428	25,684
Milk per cow (100 lbs./head)	207	204	147
Milk cow mortality rate	0.061	0.067	0.055
Total costs per unit ($/100 lbs.)	24.27	23.47	26.49
Net returns per unit ($/100 lbs.)	-6.13	-5.24	-7.56
Observations	184	156	59
Large (5,000,000 lbs. ≤ milk)			
THI load	2,748	7,879	19,348
Milk per farm (100 lbs.)	136,443	198,811	215,931
Milk per cow (100 lbs./head)	228	226	185
Milk cow mortality rate	0.067	0.067	0.075
Total costs per unit ($/100 lbs.)	20.06	19.71	21.13
Net returns per unit ($/100 lbs.)	-1.88	-2.67	-2.21
Observations	100	75	51

THI load is measured in humidity-adjusted degree hours. Farm size is measured in pounds of milk produced.

Source: 2010 USDA Agricultural Resource Management Survey, Dairy Cost and Returns Report

The results imply that dairies operated with average technical efficiency of 83.9 percent in 2005 and 85.2 percent in 2010. That is, farmers produce only about 84-85 percent of what they could if they operated on the production frontier. Of course, there is substantial variation across farms, and the measure of technical efficiency has a standard deviation of 12 percent in both years. In the inefficiency equation, the sign (but not the magnitude) of the coefficients can be interpreted as the effect on inefficiency. A positive coefficient indicates that an increase in the variable increases inefficiency or equivalently would decrease technical efficiency (see fig. 9 for an illustration of these concepts).

The results indicate that larger operation size and greater specialization in the dairy enterprise are associated with higher efficiency. Also, higher operator's age is associated with a decrease in efficiency, implying that younger farmers are more efficient. While age is significant, the number of years the operation has been producing milk has no statistically significant effect on efficiency. Operator age may be a better predictor of the vintage of the production technology than years of experience if younger farmers are more likely to invest in and operate newer buildings and machinery.

Table 5
Stochastic Production Frontier estimates—key coefficients

	2005	2010
	Output (log milk produced)	
Constant	0.199***	0.171***
	(0.031)	(0.031)
Log Milk cows	0.634***	0.674***
	(0.026)	(0.034)
Log Feed	0.207***	0.191***
	(0.017)	(0.027)
Log Labor	0.017	0.004
	(0.011)	(0.015)
Log Capital	0.009	0.017
	(0.014)	(0.012)
Log Other inputs	0.148***	0.111***
	(0.014)	(0.019)
	Inefficiency	
Constant	-3.770***	-4.423***
	(0.460)	(0.456)
College graduate	0.071	0.244
	(0.128)	(0.159)
Log operator age	1.127***	0.901*
	(0.398)	(0.531)
Log years producing milk	-0.035	-0.020
	(0.145)	(0.146)
Log operation size	-0.957***	-1.267***
	(0.116)	(0.189)
Dairy share	-3.700***	-7.381***
	(1.095)	(1.147)
THI load - average	0.087***	0.096***
	(0.013)	(0.018)
THI load - deviation	-0.005	0.047
	(0.091)	(0.079)
Observations	1,236	1,123

Note: Significant at the 10% (*), 5% (**), and 1% (***) levels. See table 3 for variable description.

Source: USDA Economic Research Service estimates using 2005 and 2010 USDA Agricultural Resource Management Survey, Dairy Cost and Returns Report.

Of greatest interest for this study, the results indicate that typical heat stress (longrun average THI load) is correlated with lower efficiency. The parameter associated with unexpected heat stress (deviation from average THI load) is not statistically significantly different from zero. There may be no significant weather effect because the model includes variables that account for variation in production across regions, and within regions, producers experience similar weather shocks.

The effect of the average THI load on inefficiency is about 10 percent larger for the 2010 sample than the 2005 sample. Hence, the estimated effect of average heat stress on efficiency was similar for both surveys despite the fact that only about 6 percent of the dairies appeared in both surveys, and despite changes in average farm size, geographical concentration of production, and production technologies over the 5 years between surveys.

Value of Lost Production From Current Heat Stress

While we are primarily interested in the implications of climate change, it is possible to use the cross-section model to estimate the current (2010) value of lost production because of heat stress. To do so, we predict technical efficiency for each operation when the THI load is zero—i.e., in a hypothetical climate with no heat stress. We then multiply the predicted percentage change in efficiency by current milk production to estimate how production would change, holding everything constant except the THI load.

Using the 2010 model parameters, we estimate that heat stress lowers annual milk production for the average dairy farm by about 1,827 cwt, or about $39,100 at 2010 prices. Scaling up using the ARMS sample weights, this is equivalent to $1.20 billion per year in lost production for the entire dairy sector.[11] For context, the sale of milk and other dairy products in the United States totaled $31.8 billion in 2007 (USDA, 2009). This loss estimate takes into account the actual heat abatement expenditures by dairy producers. For comparison, St-Pierre et al. (2003) estimated economic losses from heat stress for the dairy sector ranging from $1.09 billion to $1.82 billion (in 2010 dollars), depending on the assumptions about the level of heat abatement.[12]

[11]These estimates assume no adjustments in milk price in order to permit a better comparison with St-Pierre et al. In fact, heat stress lowers milk production, which raises the equilibrium milk price. The higher price induces an increase in output (compared to if the price stayed the same). Hence, allowing for price adjustments would reduce the estimated output effect from heat stress. Market adjustments are accounted for in the estimates of the effects of climate change presented in the next section.

[12]St-Pierre et al. (2003, p. 67) estimate economic losses of $1.51 billion (in 2002 dollars) with no heat abatement and $0.90 billion (in 2002 dollars) with “optimal” heat abatement. The authors do not observe heat abatement levels, so their estimate of actual losses is bounded by these two values. We update these estimates to 2010 prices to obtain $1.09 billion and $1.82 billion.

Climate Change Simulations

Predicted Effects in 2030

Using the estimates of the relationship between the average THI load and technical efficiency, we can forecast how production will change because of an increase in average THI load. First, we estimate the percentage change in technical efficiency using the predicted 2030 THI loads and the estimated 2010 model parameters. We then multiply the predicted percentage change in efficiency by 2010 milk production to estimate how milk production would change, holding everything constant except the THI load. This provides an estimate of the production response if there were no change in prices, inputs, technology, or location of production. Later, we explore how the results change if dairy production shifts to cooler regions in response to climate change.

For the sample of dairies surveyed in 2010, the average annual temperature is forecast to increase between 1.45 and 2.37 degrees Fahrenheit by 2030, depending on which climate model is used (table 6). The THI load is predicted to increase by an average of 1,668-3,945 humidity-adjusted degree hours. The warmer climate is estimated to reduce milk production for the average dairy by 0.60 to 1.35 percent, depending on the climate model (table 6). For the average dairy, the value of this lost production is between about $2,000 and $5,000 (at 2010 prices). Almost all (99.8 percent) dairies would experience some production loss, and 4 to 18 percent of operations (depending on the climate model) would experience a loss greater than 2 percent. With no market adjustment, the aggregate annual value of this climate change-induced reduction in milk output for the entire U.S. dairy sector is $79 to $199 million (valued at 2010 prices). This represents 6 to 17 percent of the total value of production lost in 2010 because of heat stress ($1.20 billion).

In theory, prices should respond to a climate-induced contraction in the milk supply, which would affect costs for producers and consumers. A reduction in output would lead to higher milk prices (lower technical efficiency reduces what can be produced with the same inputs.) Producers would be worse off, despite higher prices, because of their higher production costs. Consumers would also be worse off because they face higher milk prices.

The extent of the milk price increase and the magnitude of the welfare losses depend on how responsive consumers and producers are to prices. With a midlevel supply elasticity of 0.75 and relatively inelastic milk demand (E_D = -0.5), the quantity response to the milk supply shift is smaller and the price response is larger compared with a more elastic demand (E_D = -1.0) ((table 6).[13] With relatively inelastic demand, the value of the total reduction in milk production ranges from $32 million to $81 million, depending on the climate model. For more elastic demand, the range is $46 to $116 million. With relatively inelastic demand, consumers fare worse than producers; with more elastic demand, consumers fare better. Estimates of the total annual welfare losses from climate change-induced heat stress range from $106 million to $269 million, depending on the climate model.

To explore whether some regions are likely to incur greater costs from climate change-induced heat stress, we estimate production losses at the State level (fig. 10). States are grouped into the seven

[13]These elasticities are in the midrange of values reported in the literature (Schmit et al., 2002; Andreyevaet al., 2010; Davis et al., 2012; Tauer, 1998). See Key and Sneeringer (2014) for details about the consumer and producer welfare calculations.

Table 6

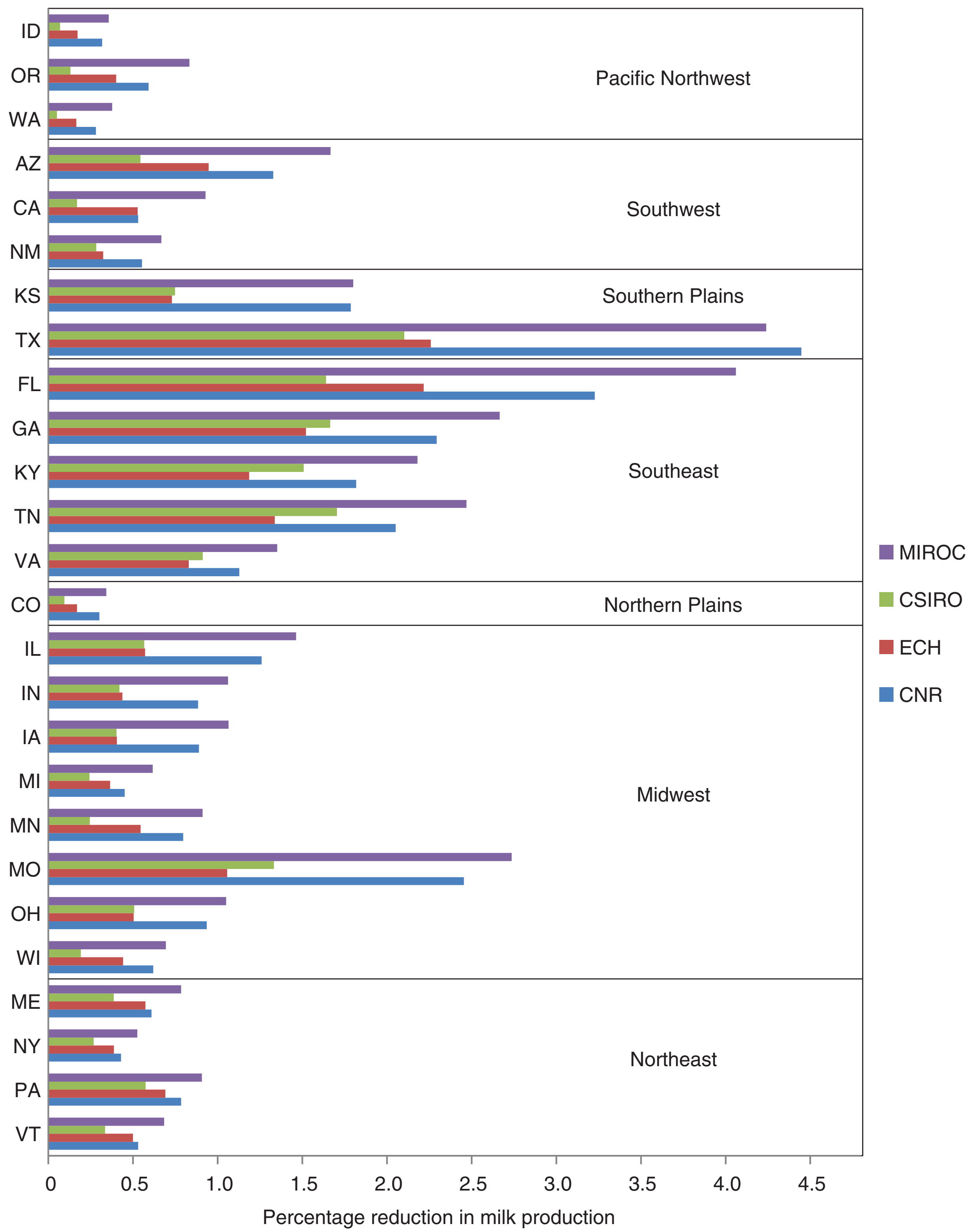
Predicted changes in climate and milk production, 2010 to 2030

	Climate model			
	CNR	ECH	CSIRO	MIROC
Change in select climate variables				
Average annual temperature (ºF)	1.61	1.45	1.23	2.37
Maximum temperature, July (ºF)	1.48	1.38	1.17	2.27
Minimum temperature, July (ºF)	1.75	1.51	1.29	2.48
THI load (Adj. degree-hours)	3,403	2,234	1,668	3,945
Percent change in quantity of milk produced (no market response)				
Mean	-1.18	-0.80	-0.60	-1.35
Standard deviation	6.98	4.17	3.98	7.43
Minimum	-18.07	-9.45	-9.16	-17.25
Maximum	2.89	2.89	2.89	2.89
Change in value of milk produced ($) (2010 price, no market response)				
Mean	-4,163	-2,854	-1,995	-4,996
Standard deviation	72,778	47,616	33,334	89,807
Minimum	-525,121	-352,948	-207,008	-710,821
Maximum	6,146	6,146	6,146	6,146
Total milk production (million cwt)				
2010	1,200	1,200	1,200	1,200
2030 (No market response)	1,190	1,193	1,195	1,188
2030 (E_D = -0.5, E_S = -0.75)	1,196	1,198	1,198	1,195
2030 (E_D = -1.0, E_S = -0.75)	1,194	1,196	1,198	1,193
Change in total value of milk production ($ million)				
2010 price (No market response)	-165.5	-113.5	-79.3	-198.6
2030 price (E_D = -0.5, E_S = -0.75)	-67.6	-46.0	-32.0	-81.4
2030 price (E_D = -1.0, E_S = -0.75)	-96.2	-65.6	-45.7	-115.8
Welfare change, (E_D = -0.5, E_S = 0.75) ($ million)				
Consumer surplus change	-134.0	-91.5	-63.8	-161.2
Producer surplus change	-89.3	-61.0	-42.5	-107.5
Consumer + producer surplus change	-223.3	-152.5	-106.4	-268.6
Welfare change, (E_D = -1.0, E_S = 0.75) ($ million)				
Consumer surplus change	-95.5	-65.3	-45.5	-114.8
Producer surplus change	-127.3	-87.0	-60.7	-153.1
Consumer + producer surplus change	-222.8	-152.3	-106.2	-267.9

Note: CNR, CSIRO, ECH, MIROC refer the General Circulation Models used to generate the climate scenarios. See data section and online appendix for details. “No market response” means there is no accounting for the fact that milk prices would increase if the supply contracts because of heat stress. How much the price increases, and how consumers and producers are affected depends on the responsiveness of consumers and producers to price (i.e. on the demand and supply elasticities, E_D and E_S).

Figure 10

Predicted annual reduction in milk production from Cimate Change-Induced Heat Stress, by USDA Regional Climate Hub and State, 4 Climate Change Prediction Models, 2030



Notes: Only States included in the 2010 Agricultural Resource Management Survey (ARMS) dairy operation survey are shown. Information about the USDA's Regional Climate Hubs can be found at http://www.usda.gov/oce/climate_change/regional_hubs.htm.

Source: USDA Economic Research Service calculations using USDA ARMS and other data.

USDA Regional Climate Hubs.[14] Milk production losses, by State, range from 0.05 percent to 4.4 percent, depending on the climate model. Production in several States in the Southern Plains and Southeast (Florida, Georgia, Kentucky, Tennessee, and Texas), as well as in Missouri, are predicted to decline by more than 2 percent by at least one climate model. For individual States, there is substantial variation across models in predicted effects, reflecting differences in climate change predictions across the GCMs (Malcolm et al., 2012).[15] Nonetheless, States in the Southern Plains and Southeast are predicted to experience the largest percentage declines in milk production, generally corresponding to the proportional increase in THI load (fig. 8).

Alternative Scenarios

The estimates of the future effects of climate change on technical efficiency assume no changes in available production technologies, producer characteristics, or location of production. In reality, climate change could induce the development of new technologies or shifts in production to regions less affected by climate change. Even without any direct responses to climate change, the size and location of dairy operations are likely to be different in 20 years. First, we explore how the effects of climate change might differ if past trends in farm size and location continue. Then we simulate a hypothetical response to climate change in which production shifts from States experiencing large increases in THI load to States experiencing smaller increases.

To project the impact of predicted future THI loads under further consolidation and continued geographic shifts, we use 1992 and 2007 Census of Agriculture data (2007 was the most recent census available at the time this analysis was conducted) to calculate the annual average growth rate in dairy production for every State. We use these State-level growth rates and the 2010 ARMS milk production data to forecast production in every State in 2030. We estimate that by 2030, U.S. milk production will have increased by 38.7 percent and average farm size will have increased by 25.6 percent, relative to 2010 (table 7).

To examine the correlation between predicted production changes and predicted climate change, we sort States into four groups according to their average predicted increase in THI load from 2010 to 2030: Group 1 (THI load increase less than 2,300 humidity-adjusted degree hours), Group 2 (2,300-3,300), Group 3 (3,300-5,000), and Group 4 (more than 5,000 degree hours). The predicted increase in THI load is positively correlated with the current THI load—that is, warmer States are predicted to experience a larger increase in THI load (table 7). The summary statistics do not show a clear correlation between farm size and THI load or between farm size and predicted change in THI, nor is there an obvious relationship between predicted increase in production and the 2010 THI load or predicted increase in the THI load.

Table 7 shows the estimated effect of climate change in 2030 using two different baselines for 2030: (1) 2010 production (also used in table 6), and (2) predicted 2030 production with no climate change and a continuation of industry growth patterns. As expected, the negative efficiency effects are higher in States having a greater predicted increase in THI load. For the average climate prediction (across the four climate models), production in States experiencing the largest increase in THI

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[14]Information about the USDA Regional Climate Hubs can be found at http://www.usda.gov/oce/climate_change/regional_hubs.htm.

[15]GCMs differ widely in the numerical methods used and in the spatial resolution of their climate projections. Consequently, the magnitude of the temperature change predictions vary widely across the models at a given location and time (Malcolm et al., 2012).

Table 7
Predicted effects on milk production under alternative assumptions about geographical shifts in production

	Average predicted increase in THI load				
	Group 1	Group 2	Group 3	Group 4	All
Characteristics, 2010					
Aver. pred. increase in THI load	1,724	2,363	3,227	5,861	2,812
Average THI load, 2010	2,153	3,394	5,661	12,645	4,661
Farm Size (cwt)	37,238	21,569	47,814	28,175	30,193
Total milk prod. in region (m. cwt)	272.7	438.1	360.4	129.1	1,200.3
Region's share of all prod. (%)	22.7	36.5	30.0	10.8	100.0
Predicted characteristics, 2030 with no climate change					
Farm size (cwt)	47,248	22,474	64,311	37,201	37,928
Total milk prod. in region (m. cwt)	442.1	473.3	588.5	161.2	1,665
Prod. increase from 2010 (%)	62.1	8.0	63.3	24.9	38.7
Region's share of all prod. (%)	26.5	28.4	35.3	9.7	100.0
Change in production in 2030 because of climate change (%)					
Baseline: 2010 production	-0.56	-0.73	-0.87	-1.88	-0.85
Baseline: predicted 2030 production	-0.60	-0.72	-0.89	-2.02	-0.86
Scenario 1: Change in production in 2030 because of:					
Geographical shift only	16.38	16.38	-20.00	-20.00	0.00
Geo. shift and climate change	15.68	15.54	-20.71	-21.62	-0.83
Scenario 2: Change in production in 2030 because of:					
Geographical shift only	3.32	0	0	0	0.88
Geo. shift and climate change	2.70	-0.72	-0.89	-2.02	0.00
Observations	255	247	293	328	1,123

Notes: "Climate change" in this table refers to the average forecast from the four climate models. The Groups are defined at the state level according to predicted changes in long run THI load (humidity adjusted degree hours): Group 1 ($\Delta THI_{LR} < 2300$) Idaho, Maine, Michigan, New York, Oregon, Vermont, Washington; Group 2 ($2300 \leq \Delta THI_{LR} < 3300$) Colorado, Minnesota, Pennsylvania, Wisconsin; Group 3 ($3300 \leq \Delta THI_{LR} < 5000$) (California, Illinois, Indiana, Iowa, Ohio, Virginia; Group 4 ($5000 \leq \Delta THI_{LR}$) Arizona, Florida, Georgia, Kansas, Kentucky, Missouri, Tennessee, Texas.

(Group 4) is predicted to decline by 1.88 percent relative to the 2010 baseline and by 2.02 percent relative to the predicted 2030 baseline with no climate change. In contrast, production in States with the smallest increase in THI load (Group 1) decline by only 0.56 percent and 0.60 percent, respectively. The percentage-point declines in total production (average of all 4 THI groups) relative to the two baselines are almost identical (-0.85 percent and -0.86 percent). Of course, the absolute decline is much larger when the baseline is estimated 2030 production. In sum, we find that a continuation of recent (1992-2007) trends in the location and scale of production will not substantially alter the magnitude of the effect of climate-induced heat stress on dairy productivity.

Table 7 also illustrates two hypothetical geographical responses to climate change. Scenario 1 illustrates an adaptive response where production moves out of the States experiencing greater increases in heat. Specifically, production is assumed to decrease by 20 percent compared to the predicted 2030 baseline in States that are predicted to have the largest increases in THI load (Groups 3 and 4) and to increase by 16.38 percent in the other States (an increase such that total national production equals projections with no climate change.) Such pronounced geographic shifts are unlikely given the relatively small heat stress effects we estimate. However, the size of the shifts falls within the range of the predicted production changes between 2010 and 2030.

Compared to the 2030 baseline, the shift in production to regions less affected by climate change mitigates the total effect of climate change. However, the mitigation is very small—total milk production falls by 0.83 percent compared to 0.86 percent. The mitigation effect is small mainly because the predicted increases in the THI load in Groups 1, 2, and 3 are relatively similar, so the benefits from shifting production are limited. Dairies in Group 4 are predicted to experience a much larger average increase in THI load than the other regions, but Group 4 produced only 9.7 percent of national milk output in 2010.

Scenario 2 (table 7) illustrates how an increase in production in one region could offset the effect of climate change. Shifts in production from one State to another cannot completely offset the effects of climate change since all States are negatively affected by climate change. However, if production expanded in some States because of market or policy changes, this could partially offset the negative effects of climate change. For example, consider an increase in milk production in Group 1 of 3.3 percent compared to the 2030 predicted baseline (which increases national output by 0.88 percent). This is sufficient to offset the negative climate effect (-0.86 percent). This is a relatively minor change, especially compared to the predicted increase in output (62.1 percent) between 2010 and 2030 that would have occurred without any climate change.

Discussion and Qualifications

The empirical approach used in this study extrapolates from how dairy productivity currently responds to variation in the THI load to predict future responses to climate change. As with many forecasts, this approach assumes that the currently available technologies (and other factors) do not change over time. Of course, technologies are likely to evolve over the next 20 years, which will increase overall productive efficiency and producers' ability to respond to heat stress. It is likely that heat abatement technologies will improve, more heat-resistant breeds will be developed and adopted, and production will shift to regions with cooler climates. Hence, our estimates likely represent an upper bound on the production effects from increased heat stress due to climate change. We used past trends in dairy location and production to improve our predictions of climate change impacts, and we simulated the effect of a potential response to climate in terms of regional shifts in production. However, it is difficult to accurately forecast producer responses to climate change—in terms of the operation's location, size, vintage, specialization, or technological change.

A second caveat is that we did not account for how climate might affect milk quality. In addition to reducing the quantity of milk produced, some studies have found that heat stress can lower the protein percentage and fat content of milk (Ingraham et al., 1979; Knapp and Grummer, 1991; Moore et al., 1992; Kadzere et al., 2002). To the extent that these qualities are positively correlated with milk price, our estimates would tend to underestimate the costs to producers and consumers of heat stress and, consequently, of climate change.[16]

[16]Unfortunately, it is not possible to use the price received by the producer to adjust for milk quality. This would be possible if the milk price reflected only milk quality. However, the milk price may also reflect the costs of production. If regional prices reflect local production costs, and heat stress raises production costs, then heat stress will result in higher prices. Hence, heat stress will lower milk quality, which lowers prices, but also raise production costs and milk prices. It is not possible to distinguish between these effects with the data at hand.

This analysis considered warming scenarios in 2030, only 20 years after our base year. Further into the future, temperature increases are predicted to be substantially larger. Temperatures are predicted to increase by about 1-2ºF (0.6-1.1ºC) in most of the United States by 2020, compared to a base year of 2000 (USGCRP, 2009). Temperatures are predicted to increase about 2-6ºF (1.1-3.3ºC) by 2050, and by 3-10ºF (1.7-5.6 ºC) by 2100, depending on the region, emissions scenario, and climate model used (USGCRP, 2009).

Higher temperatures in the more distant future would mean higher THI loads, and consequently, greater reductions in dairy technical efficiency. While it would be possible to use our approach to simulate the effect of longer range temperature scenarios, there is substantial uncertainty surrounding long-range climate predictions.[17] Additionally, since our approach does not account for changes in technology or the location of operations—and since these factors would likely evolve over time in response to increasing heat stress—predictions based on the approach used in this report would be of limited value for very long-range analyses.

[17]Temperature changes in the next couple decades are primarily determined by past emissions of GHGs, and there is relatively little variation in projected temperature across models over this period. In contrast, temperature increases after the next couple decades will be determined primarily by future GHG emissions, which makes future climate predictions more uncertain.

Conclusion

Based on an analysis of U.S. dairies located in a wide variety of climates, we find a negative relationship between average heat stress (THI load) and technical efficiency. Estimates of the stochastic production function model indicate that an increase in THI load of 1,000 degree hours implies about a 0.38-percent decrease in milk production. We use this result and forecasts from four climate models to estimate the amount of production that will be lost from the additional heat stress caused by global warming, holding all else equal. We estimate that in 2030, with no market response, the additional heat stress will lower milk production for the average dairy by 0.60 to 1.35 percent, depending on the climate model. In some States, mostly in the South, the average dairy will experience production declines greater than 2 percent. Allowing for higher market prices resulting from the contraction in production, we estimate total annual welfare costs of climate change-induced heat stress of $106 to $269 million. Because we assume that operators do not respond to environmental changes—e.g., by adopting new technologies or breeds, or by changing location—these estimates are upper bounds on likely output effects and costs. The estimates do not take into account the effect of the 2014 Farm Act or other policy changes.

Valued at 2010 prices, we estimate that heat stress currently reduces milk production by $1.20 billion per year compared to a hypothetical climate scenario with no heat stress. Despite these substantial costs, U.S. dairies operate in diverse climates, including very warm regions in the South. This suggests that other factors (e.g., input prices, output prices, distance to markets, policies, etc.) in addition to climate are important in determining the location of production. While heat stress appears to be an important determinant of technical efficiency, it is just one of many factors influencing productivity and profitability.

While the scale of the estimated production effects from climate change in 2030 is modest, over a longer time horizon climate change is likely to be much more extreme and could result in substantially higher THI loads and efficiency losses. It is worth emphasizing that this study did not consider other potential costs of climate change for the livestock sector. Climate change will likely alter the price and availability of feed crops, the location and productivity of pasture and rangeland, and the distribution of livestock parasites and pathogens. Estimating the magnitude of these potential effects is an important area for future research.

Because climate change occurs gradually, it should be possible to mitigate some of the negative consequences for livestock production through research into and development of adaptive technologies and practices. Possible innovations to address climate change-induced heat stress include more energy-efficient cooling for animal housing, improved heat tolerant breeds, and improvements in scientific knowledge about the interactions between feed, nutrition, and heat stress. USDA supports agricultural research on climate change adaptation and recently formed seven Regional Hubs for Risk Adaptation and Mitigation to Climate Change. The Climate Hubs have the goal to help farmers cope with the consequences of climate change and represent a partnership with public and land-grant universities, Cooperative Extension, USDA researchers, the private sector, and State/local/regional governments.

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Appendix A—Stochastic Production Frontier Model

The stochastic production frontier approach has been widely used to estimate the technical efficiency of a variety of crop and livestock production systems (e.g., Ahmad and Bravo-Ureta, 1996; Kumbhakar and Heshmati, 1995; Cabrera et al., 2010; Mayen et al., 2010). Despite the substantial effect of heat stress on milk production, few studies of dairy productivity and efficiency have accounted for weather or climatic conditions. An exception is Mukherjee, Bravo-Ureta, and De Vries (2013), who included a heat index in a stochastic frontier model and found that it had a significant negative correlation with milk production for dairies in Florida and Georgia.

To estimate the effect of the THI load on technical efficiency, we use the stochastic frontier production function model first proposed by Aigner et al. (1977) and Meeusen and van den Broeck (1977). Stochastic frontier models have a two-part error term composed of a symmetric disturbance, representing measurement error and other random factors, and a one-sided random variable representing technical inefficiency:

(A1) $$\ln(q_i) = f(\boldsymbol{x}_i\,\beta) + v_i - u_i,$$

where q_i is the observed output of farm i and $f(\boldsymbol{x}_i,\beta)$ is the maximum quantity that can be produced with $\boldsymbol{x}_i$ (a vector of inputs) and a technology described by the parameters β. Production can deviate from this deterministic frontier because of random shocks v_i (which could be positive or negative) or because of productive inefficiency u_i, which reduces output $u_i \geq 0$.

The technical efficiency of farm i (TE_i) is defined as the ratio of its observed output to its feasible output (on the stochastic frontier):

(A2) $$TE_i = \frac{q_i}{\exp\left(f\left(\boldsymbol{x}_i,\beta\right)+v_i\right)} = \exp\left(-u_i\right).$$

This measure ranges between zero and one, with one being fully efficient.

Estimating the model requires assumptions about the error distributions. We use the common "normal/half-normal" specification, which assumes v_i is independently distributed $N\left(0,\sigma_v^2\right)$ and u_i is independently distributed half-normal $N^+\left(0,\sigma_u^2\right)$. The half-normal distribution has a density of zero for negative values of u_i, an expected value of $\sigma_u\sqrt{2/\pi}$, and a variance equal to $\sigma_u^2\left(1-2/\pi\right)$.

Letting $y_i = \ln(q_i)$, and $f(\boldsymbol{x}_i, \beta) = \boldsymbol{x}_i'\beta$, the log-likelihood function for the model is:

(A3) $$\ln L\left(y_i \middle| \beta,\sigma,\lambda\right) = \sum_{i=1}^{N}\left\{\frac{1}{2}\ln\left(\frac{2}{\pi}\right) - \ln\sigma + \ln\Phi\left(-w_i\right) - \frac{\varepsilon_i^2}{2\sigma^2}\right\},$$

where $\sigma^2 = \left(\sigma_u^2+\sigma_v^2\right), \lambda = \sigma_u/\sigma_v, \varepsilon_i = y_i - x_i{}'\beta, w_i = \varepsilon_i\lambda/\sigma$, and $\Phi(\cdot)$ is the standard normal cumulative distribution function (Aigner et al., 1977). The data do not permit a direct estimate of the disturbance u_i because we can only observe (given an estimate of β) the difference between the random terms, $v_i - u_i$, which is equal to ε_i. However, Jondrow et al. (1982) showed that conditional on ε_i, u_i can be approximated:

(A4) $$E\left[u_i \mid \varepsilon_i\right] = \frac{\sigma\lambda}{1+\lambda^2}\left[\frac{\phi\left(w_i\right)}{1-\Phi\left(w_i\right)} - w_i\right].$$

One approach to estimating how the THI load and other exogenous factors affect technical efficiency is to first estimate efficiency without accounting for these exogenous factors, and then explain the variation in efficiency in a second step. This two-step approach can, however, result in biased and inefficient estimates (Wang and Schmidt, 2002). An alternative approach is to incorporate the determinants of technical efficiency directly into the model and estimate the model in a single step. We implement the single-step approach by defining the variance of the underlying half-normal distribution σ_u^2 as a function of observable factors z_u and a set of parameters δ_u:

(A5) $$\sigma_{ui}^2 = \exp\left(z_{ui}'\delta_u\right).$$

With this specification, the factors z_{ui} affect the mean and variance of the inefficiency term u_i, and the estimate of technical efficiency, which is derived from (A4).

In our specification, we assume that climate (measured using the THI load) affects technical efficiency but not the production frontier—the technical relationship between inputs and outputs. This specification is justified if the THI load is not an input and does not directly affect the production technology. However, the THI load does affect input productivity—higher THI loads cause lower rates of weight gain and milk production, holding inputs constant. Producers can mitigate output losses by increasing expenditures on capital (buildings and cooling systems), energy (to operate cooling systems), or feed. Increasing inputs to compensate for higher THI loads lowers factor productivity relative to what it would be in the thermoneutral zone. Hence, while operators in regions with higher THI loads have technology similar to that used by operators in regions with lower loads, heat stress will make them less technically efficient—that is, they will operate further from the production frontier.

Appendix B—Predicted THI Loads

Malcolm et al. (2012) use the Jones et al. (2009) downscaled data to compute the average monthly values for maximum and minimum temperatures on agricultural land within 48 Regional Environment and Agriculture Programming (REAP) regions. To use these data, we first scale these estimates to the county level using a REAP-to-county crosswalk. Some counties are in more than one REAP region; when this is the case, we use the portion of the county that is in the REAP region to weight predictions. Refer to these predictions as $PMin_{cm}$ and $PMax_{cm}$, where c refers to county and m to month. These are the predicted changes between 2000 and 2030 in temperature minimum and maximum by county and month.

To estimate the long-term THI load in 2030, we make use of the grid-cell-level daily dew point and temperature minima and maxima for 1990-2005 (Schlenker and Roberts, 2009). We first merge the predictions to this grid cell data by county to provide $PMin_{gm}$ and $PMax_{gm}$, where g refers to grid cell. We next calculate predicted THI minima and maxima for each day, d, between 1990 and 2005 ($PTHIMin_{gdmy}$ and $PTHIMax_{gdmy}$) using the following equations:

(B1) $$PTHIMin_{gdmy} = \left(Min_{gdmy} + PMin_{gm}\right) + [0.36 \times \left(Dew_{gdmy} + PMin_{gm}\right)] + 41.2.$$

(B2) $$PTHIMax_{gdmy} = \left(Max_{gdmy} + PMax_{gm}\right) + [0.36 \times \left(Dew_{gdmy} + PMin_{gm}\right)] + 41.2.$$

Using these predicted THI minima and maxima, we calculate the predicted daily THI load for each day between 1990 and 2005 ($PLoad_{gdmy}$).

We next sum the daily estimates to arrive at the annual predicted THI load for each year between 1990 and 2005:

(B3) $$PLoad_{gy} = \sum_{d} PLoad_{gdmy}.$$

We then find the average across all years between 1990 and 2005 to find the expected THI load in 2030:

(B4) $$PLoad_{g} = \frac{1}{16} \sum_{y} PLoad_{gy}.$$