Extreme Heat and Livestock Production: Cost and Adaptation in the US Dairy Sector

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Abstract

Climate change poses a threat to global livestock production as extreme weather conditions become more frequent. We quantify the impact of heat stress on the dairy industry throughout the Midwestern United States in the years 2012-2016 using animal-level production data. When temperature and humidity increase above critical levels, dairy cows become heat stressed and eat less which causes a drop in milk production. We estimate a total of $174 million in lost revenue over a five year period. These losses are mostly due to moderate-intensity heat events, though we find the largest per-event losses following high-intensity events. Losses are largest on small farms, while large farms appear to mitigate the effects of low-intensity heat events. Crucially, certain types of dairy cattle are more susceptible than others: dairy cows that have given birth multiple times and are early in their production cycle are the most productive but also the most vulnerable to heat stress. We estimate that these cattle lose about between 3-6% of their milk production in a heat wave as opposed to at most 2% for other cattle.

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1 Introduction

The dairy industry faces an impending challenge: increasingly frequent extreme heat events due to climate change [IPCC, 2022]. Dairy production is especially vulnerable to heat events since cattle experience "heat stress" at high levels of temperature and humidity. Heat stressed cattle eat less, which causes their milk productivity to drop [Key et al., 2014, St-Pierre et al., 2003, West et al., 2003].

Protecting livestock agriculture from climate change is a global imperative as it contributes 40% of agricultural production in high-income countries and 20% in low-income countries [Food and Agriculture Organization of the United Nations, 2021]. As a low-cost protein source for smallholder farmers and low-income populations worldwide, dairy is critical for global food security [Tricarico et al., 2020]. Moreover, dairy products are a source of key nutrients (e.g., calcium, vitamins B12 and B5, and magnesium) for vulnerable groups like pregnant women and children [Tricarico et al., 2020].

The impacts of heat stress on dairy production has been quantified using state-level data aggregated to the monthly or annual level [Gisbert-Queral et al., 2021, St-Pierre et al., 2003]. These estimates have two shortcomings. Without a daily measure of milk production, it is difficult to understand the precise impacts of heat waves on milk production. Second, these data simply reflect herd size, masking heterogeneity in cows' vulnerability to heat stress within and across calving cycles. Dairy farmers may optimize the timing of births to minimize costs associated with heat stress, but this form of adaptation is not possible to detect when production data is aggregated. Farm-level data from a limited number of herds [Bohmanova et al., 2007, Key et al., 2014] offer insight into the biological impacts of heat stress but do not offer an industry-wide estimate of losses.

Our research fills these gaps by using a novel data source to study the short-run impacts of heat stress. We pair panel data on cow-level milk production collected every month for 18,000 dairy farms throughout the Midwestern United States with daily temperature and humidity data. We estimate that the herds in our sample lost 975 million gallons of energy-adjusted milk and $174 million in revenue over five years due to heat stress.

Dairy cattle experience heat stress at THI levels above 72 THI [Armstrong, 1994]. Despite this, we find minimal losses when weather conditions are equivalent to 72 - 80 THI. Impacts are heterogeneous across farm size, with small farms losing production even under these low-stress conditions while larger farms only experience losses during medium- or extreme-stress conditions. Similarly, some states experience no losses under low-stress conditions, but almost all states are impacted by extreme stress.

We produce the first large-scale estimates of the changing impact of heat stress over a cow's year-long production cycle. We find that heat stress vulnerability coincides with the most productive phases in a cow's lactation cycle: cows that have recently given birth given birth and have given birth more than once. These cows account for half of the total losses in our sample.

Our results have significant implications for understanding the impact of heat stress and adaption in the US dairy sector. We find smaller per-cow losses than expected based on the dairy science literature and heterogeneous effects across farms. This suggests that some farmers have adapted to mitigate low-stress days, but adaptation does not yet protect from extreme conditions. Losses are likely to significantly increase in a scenario with more extreme events. Moreover, we highlight that the most productive cows are the most vulnerable to heat stress. We discuss a number of options for management, including timing the births of second and subsequent calves to mitigate heat exposure in a cow's most vulnerable period.

2 Results

2.1 Cows are protected from low-stress heat events but vulnerable to medium- and extreme-stress days

We first follow the literature and estimate the average impact of heat stress across all cows in our sample. We classify days based on total heat load (estimation details in section 4) and divide them into no stress (no heat load) low-stress (positive heat load below 70), medium stress (70 - 140 heat load), and extreme stress ($>$ 140 heat load). Figure 2 panel a shows the impact of the day's heat load on the same day's milk production. Low levels of heat load reduce milk production at most by .5% while moderate levels of heat load double the effect to 1%. Extreme heat loads reduce milk yield by 2%.

The impacts of heat load persist up to a week after the event (Figure B5). Using our lags model, we calculate that one day of heat load exposure over 140 reduces that week's milk production by 7.2% (Table 1). We also examine the impact of cumulative exposure to heat load by estimating the impact of multiple days of heat stress within an 8-day period. Figure 3 shows the cumulative impact of multiple days above three levels of heat load: above 0, above 70, and above 140. The effects are non-linear; the effect of a single day above 0 heat load is insignificant, while the the seventh day has a marginal effect of a 1% loss in milk yield. These non-linear impacts show that heat waves are particularly damaging to milk production.

2.2 Losses vary across space and farm size

Our results are not purely biological effects. Instead, they are the impacts of heat stress mitigated by management and capital investment made by farms to lessen heat stress. Figure 2 panel b shows how heat load impacts differ across herd sizes. We expect that larger dairy farms may have more resources to invest in machinery such as fans and sprinklers and should be the least impacted by heat stress (see supplement for a thorough discussion of management practices that reduce heat stress).

Our estimates confirm this. The effects of heat load are decreasing in herd size, and the largest dairy farms, those above five hundred cows, experience no damages from low levels of heat load. All herd sizes experience significant drops in milk yield under medium stress, although the smallest herds still experience a significantly higher loss than the largest herds. For days with extreme stress, the size of the effects is statistically indistinguishable across herd size: all farm types experience between 2 and 4% drops in milk yield.

We also expect the impacts of heat stress to be different across the states in our sample.

Farms in states with higher exposure to heat stress may also make more investments to mitigate losses during these events. In Figure 4, we map the effect of heat stress across states. Only a few states, North Dakota, Illinois, Missouri, Michigan, and Pennsylvania, experience significant losses in milk yield at the lowest-stress level (heat load 0 - 35). As in our sample-wide estimates, we see increasing losses at higher levels of heat load. More states experience significant losses at during medium- and extreme-stress days, and states' losses increase in magnitude as heat load increases.

While nearly all states show an increase in losses as heat load increases, the increase is gradual and maximum losses are no more than 2% for some states (e.g., Michigan, Minnesota, and Pennsylvania). In these states, we expect that management practices are effective at mitigating heat stress at all levels of heat load. Notably, these are also relatively mild states. In contrast, some states do not experience any losses under low-stress conditions but high losses (up to 5%) under extreme stress conditions (e.g., Arkansas, North Carolina, South Carolina, and West Virginia). Farms in these states may have mitigated low-level heat load but are extremely vulnerable to high levels of heat load, which are common in these states.

2.3 High-yielding cows are the most vulnerable to heat stress

Next, we examine the impacts of heat stress on different cohorts of dairy cattle. Figure 5 shows the total effect of heat stress for each cohort of cows at varying levels of heat load, and supplement Table C1 reports the underlying coefficients. The highest-yield cows, those with multiple births ("Multi") and that are less than 120 days post-birth ("Early"), experience the highest losses due to heat stress. These cows lose 3% of production even under low-stress conditions and up to 6% on a day with extreme stress. Later in their cycle, cows with multiple births see minimal losses to heat stress or a very small bump in production (1% on a low stress day). In comparison, cows giving birth for the first time that are early in their cycle see a 1% reduction in milk yield regardless of heat load level. Later in their cycle, they lose from 0.4% under low stress conditions up to 2% under extreme stress conditions.

Our lag model shows that the most vulnerable cows see an 11% loss the week following an extreme heat load compared to 7.2% for the average cow. These results indicate that the average effects of heat stress are largely driven by the most productive cows in each herd and by when in the year dairy farmers decide to breed cattle.

3 Discussion

Across all of the herds in our sample, we estimate a total loss due to heat stress of 975 million pounds of energy-adjusted milk over the period (Table 1). At $20 per hundredweight, this is equivalent to $174 million in lost revenue over 5 years. While losses varied greatly year-to-year, this comes out to $34.8 million in lost revenue per year, on average. Over half (52% or $88.7 million dollars) of the total losses are due to lost yield of multiparous cows early in their cycle.

For a hundred-cow herd with an average yield of 80 pounds of energy-adjusted milk per cow and subjected to the sample average weather conditions, we estimate 143,942 pounds of energy-adjusted milk were lost to heat stress over five years. At $10 profit per pound of milk, this is equivalent to $1.4 million dollars in lost profit over five years, or $287,888 per year.

Under current climate conditions, most of the losses are due to low- and medium-stress days. The losses were composed of 263 million due to low-stress days (27% of estimated losses), 336 million due to medium-stress days (34%), and 376 million due to extreme-stress days (39%). This is due to the frequency of these events; the average county in our sample experienced 78 low-, 41, medium- and 25 extreme-stress days per year. However, the yield loss per cow due to an extreme-stress day is nearly triple that of a medium-stress day. Under climate scenarios with more frequent extreme stress days, the costs could be far higher.

We find strong evidence that some farmers have adapted to low-stress. We find smaller average impacts previous studies. We also do not find losses due to low-stress events, for which we anticipate a biological response, on large farms or in some states. We attribute this to investment in infrastructure such as sprinklers and fans as well as management practices such as timing of calving and timing of feeding during a heat event.

Our work suggests that US farmers and consumers will benefit from programs that support investment in climate-smart infrastructure. Future work should directly measure these adaptation behaviors to quantify their mitigation benefits. This information could shed light on the long-term benefits of such investments so as to support farmers in making the high fixed cost of investment.

Our work also shows that the timing of breeding decisions may have a meaningful impact on how much dairy farms are exposed to heat stress. If dairy farmers were to time breeding so that cattle experienced no heat stress in this vulnerable period, the acute impacts of heat stress would be significantly reduced, though the full impacts of this change are beyond the scope of this paper.

We demonstrate the vulnerability of livestock production, and dairy production in particular, to climate change. Despite being among the most technologically advanced in the world, US dairy producers experience significant losses from heat events. All farms in our sample remain vulnerable to extreme-stress days regardless of scale or location. This raises concerns for low-income contexts where livestock production is a main income source and dairy products are a vital source of protein and calories. Yet, the potential for investment and management to mitigate heat stress suggest there are ways for livestock producers to buffer themselves from the harmful impacts of increasing heat.

4 Methods

4.1 Data

Dairy production data comes from Dairy Records Management Systems (DRMS), a cooperative that tracks dairy production on herds that are members of a Dairy Herd Improvement Association (DHIA). We use 56 million dairy cow production records sourced from over 18 thousand dairy farms from the years 2012 to 2016. Cows are sampled monthly, so the data are a panel of daily cow-level production for each farm that is a DHIA member. Our sample for this analysis covers the states in Figure B1. About 44% of dairy farms nationwide are members of DHIAs and in our chosen states DHIA participation is about 50% [Council on Dairy Cattle Breeding, 2023]. The states in this region have similar sized dairy farms and similar climates, allowing for a more comparable production system across states.

Daily weather data comes from gridMET, which measures temperature and humidity at the 1/24th degree (4-km grid) level [Abatzoglou, 2013]. We process these to daily, county-level maximum and minimum temperature humidity index (THI) measurements Mader et al. [2006]. THI is the best measure of the stress a cow experiences, as the combination of heat and humidity limits the cow's ability to cool through sweating or other forms of evaporative cooling [Armstrong, 1994, Bohmanova et al., 2007].

Cattle are negatively impacted when THI never drops within a day, as they are unable to recover. To incorporate this, we use not just the THI max but the amount of time spent above a cow's critical THI threshhold (72), to calculate THI heat load [St-Pierre et al., 2003, Key et al., 2014].

We discretize heat load into quartiles of days with a non-zero heat load: (0 - 35], (35 - 70], (70 - 140] and 140 or above. These quartiles roughly map to the categories of heat stress based on maximum daily THI developed by Armstrong [1994] (Appendix Figure B7). Non-zero heat loads below 70 are equivalent to low-stress days (THI max 72 - 80), days with a heat load between 70 and 140 are equivalent to moderate-stress days (THI max 80 - 90), and days with heat load above 140 are equivalent to extreme stress days (THI max > 90). Section Appendix B.2 contains more information about the calculation of THI heat load and the relationship between heat load and daily THI min and max.

Figure B2 shows the distribution of heat load in the summer months (defined as May to September) of our sample. About 30% of days have zero heat load as THI max never crosses the 72 threshholds. Between 15 and 20% of days reach low levels of heat stress, and the remaining 15 and 20% of days reach moderate and extreme heat loads, respectively. Figure 1 panel a shows the stress quartile of each county's average summer heat load.

Panel b of Figure 1 shows the annual average number of days of extreme (> 140) heat load a county experiences across the five summer months. Most parts of the country experience at least 30 days of extreme heat load, while states like Missouri and South Carolina experience close to 90 days of extreme heat load. We map the total extreme heat days in a county by year in Figure B3.

4.2 Empirical Strategy

We estimate the a cow's daily production as a function of her physical environment and where she is in her production cycle. The relationship of daily milk production to the days since the cow gave birth ("days in milk" or DIM) is modeled in a lactation curve (Figure B4). Production reaches its peak in the first 120 days of a lactation cycle and is higher at every point for cows that have given birth multiple times (i.e., "multiparous" rather than "primiparous"). The lactation curve is modeled mathematically in the Wood Model as a half-gamma curve [Wood, 1967].

Following Hutchins and Hueth [2021], we adapt the Wood model to incorporate heat stress and estimate how heat stress causes deviations of milk production from the biological lactation curve.

$$ln(y_{ihct}) = f(d_{ihct}, l_{ihct}) + \sum_{p \in \mathbf{P}} \sum_{k=0}^{K} \beta_{pk} \mathbb{1}\{z_{c,t-k} \in P\} + \alpha_h + \gamma_t + \epsilon_{ihct}. \tag{1}$$

Our outcome, $ln(y_{ihct})$ measures the log milk production for cow i in herd h and county c at time t. Based on the Wood model, we include $f(d_{ihct}, l_{ihct}) = l_{it} + bln(d_{it}) - cd_{it}$ where l_{it} is the number of production cycles the cow has experienced (i.e., 1 indicates that the cow is in their first production cycle) and d_{it} is days in milk.

Our treatment is a series of dummy variables, $z_{c,t-k}$, representing THI heat load: (0 - 35), [35 - 70), [70 - 140) and 140 or more. We omit the base category of days with no heat load. We control for time-invariant herd characteristics (α_h) and month, year, and calving month fixed effects (γ_t). We cluster standard errors at the herd level.

Next, we consider the heterogeneous impacts of heat stress based on the cow's lactation cycle.

$$
\begin{aligned}
ln(y_{ihct}) =& f(d_{ihct}, l_{ihct}) + \sum_{p \in \mathbf{P}} \sum_{k=0}^{K} \beta_{pk}^{0} \mathbb{1}\{z_{c,t-k} \in p\} \\
&+ \sum_{p \in \mathbf{P}} \sum_{k=0}^{K} \beta_{pk}^{1} \mathbb{1}\{z_{c,t-k} \in p\} \times Multiparous_{ihct} \\
&+ \sum_{p \in \mathbf{P}} \sum_{k=0}^{K} \beta_{pk}^{2} \mathbb{1}\{z_{c,t-k} \in p\} \times EarlyDIM_{ihct} \\
&+ \sum_{p \in \mathbf{P}} \sum_{k=0}^{K} \beta_{pk}^{3} \mathbb{1}\{z_{c,t-k} \in p\} \times Multiparous_{ihct} \times EarlyDIM_{ihct} \\
&+ \alpha_h + \gamma_t + \epsilon_{ihct}.
\end{aligned}
\tag{2}
$$

We interact heat stress events with two indicators: multiparous (i.e., $Multiparous_{ihct} = 1$ if the cow is not in her first lactation) and whether she is early in her lactation cycle (i.e., $EarlyDIM_{ihct} = 1$ if she is less than 120 days postpartum at time t.) By interacting heat stress events with these indicator variables we are testing whether different cohorts of dairy cattle respond differently to heat stress.

We use our estimates of heat stress to calculate a back-of-the-envelope estimate of the total damages to these herds from 2012 to 2016. We sum the average loss estimates from Figure B5 for all seven lags to get a point estimate of the total yield decrease over the week following one day of heat stress. We multiply these estimates by county-by-month counts of the number of stress days with each level of heat load and the number of cows. We use the sample average winter yield, 81.8 lbs per cow, as the assumed yield for each of these days. We also calculate the yield losses from heat stress for multiparous cows early in their production cycle and multiply this by county-by-month number cows in this cohort and the cohort average yield of 98 lbs per cow.

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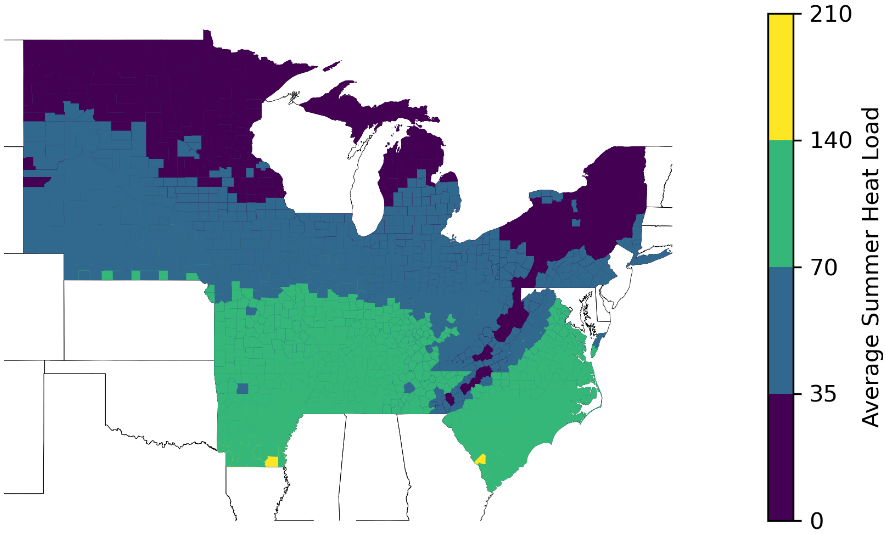
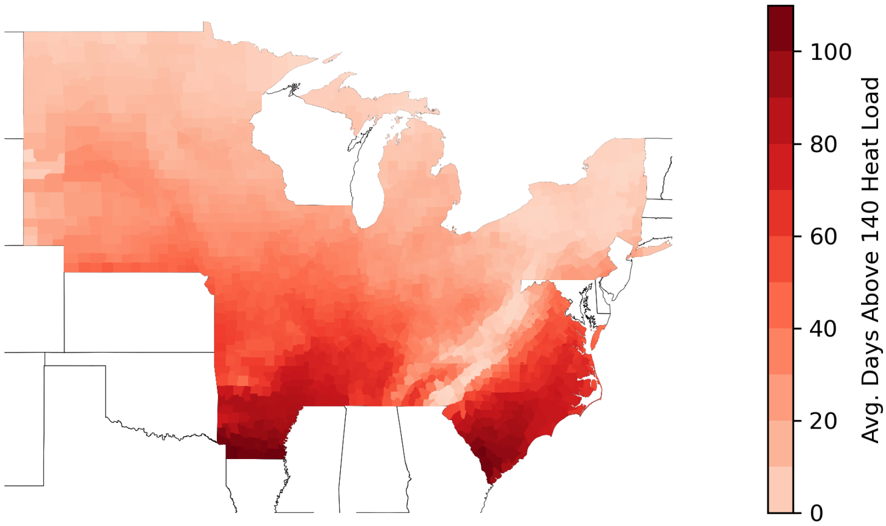


(a) Average summer heat load

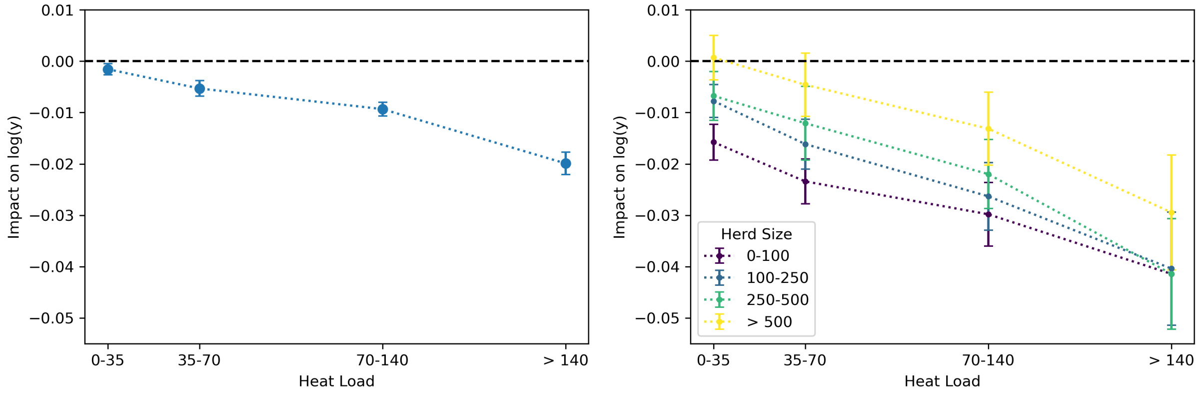


(b) Number of days above 140 heat load in the summer

Figure 1: Heat load patterns across sample states

Appendix A Background

Heat stress impacts both the production ability and health of dairy cattle. At high levels of temperature and humidity, cattle experience an increase in their body temperature which causes them to eat less [West et al., 2003]. The milk production ability of dairy cattle begins to decrease when the Temperature Humidity Index (THI) goes above 72 [Bohmanova et al., 2007, West, 2003]. Ravagnolo et al. [2000] finds that, for each unit increase above 72, milk production drops about 1%. Heat stress also makes it more difficult for cows to become pregnant [Jordan, 2003]. Each additional day a cow is not



(a) Heat Effects Across All Herds (b) Heat Effects Across Herd Size

Figure 2: Average, non-linear impact of heat load

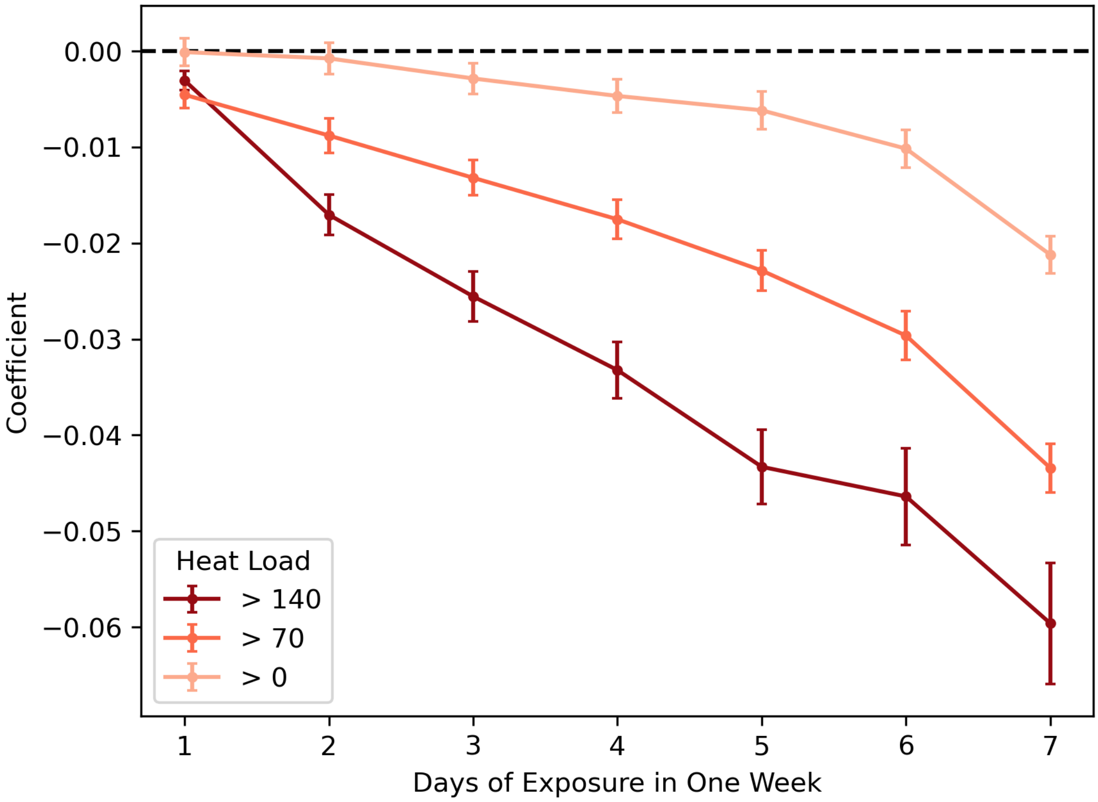
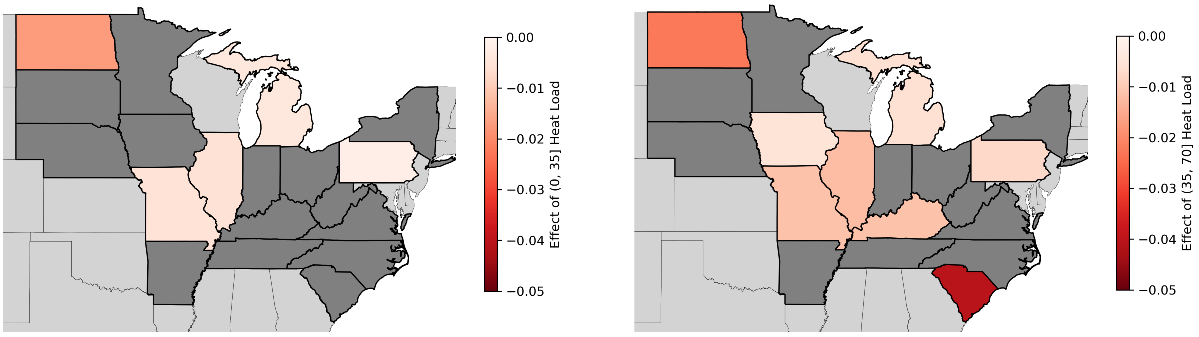
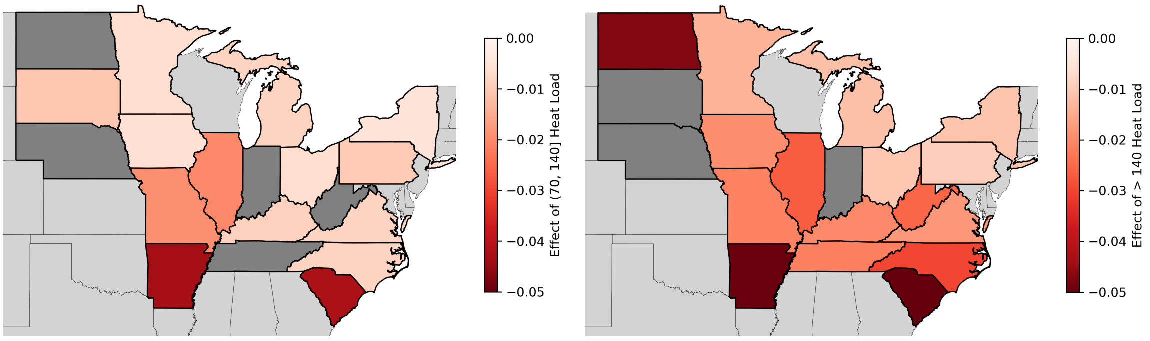


Figure 3: Multiple days of heat exposure



(a) 0-35

(b) 35-70



(c) 70-140

(d) > 140

Figure 4: State-level impacts of heat load
Note: states with coefficients not statistically different than zero at the 10% level are in gray.

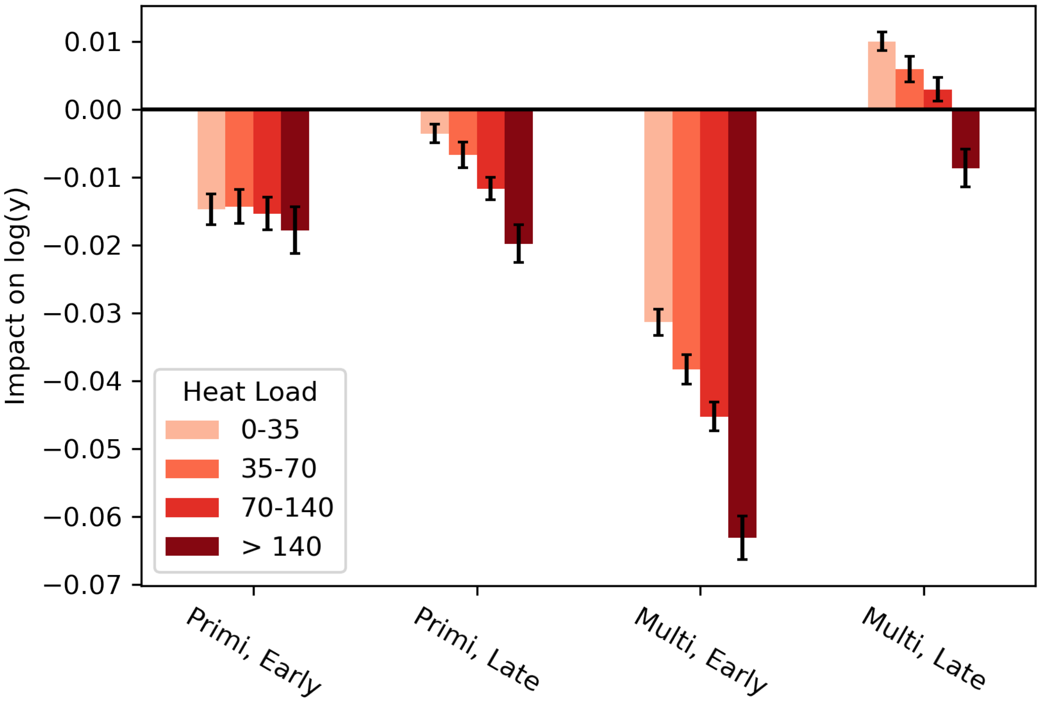


Figure 5: Effect of day-of heat load on milk yield

Table 1: Estimated Total Damages from 2012 to 2016

Heat Load	0-35	35-70	70-140	> 140	Total
All Cows					
% Reduction from 1 Day	0.40	1.70	2.60	7.20	
Yield Loss, millions lbs	72.62	190.50	335.75	376.03	974.90
Revenue Loss ($20/cwt), million USD	12.97	34.02	59.96	67.15	174.09
Highest Producing Cows					
% Reduction from 1 Day	3.70	5.60	4.10	11.10	
Yield Loss, millions lbs	114.89	134.42	120.63	127.17	497.11
Revenue Loss ($20/cwt), USD	20.52	24.00	21.54	22.71	88.77

Note: the yield loss is calculated as: Percent Loss × Number of Stress Days in Month × Number of Cows in County-Month × 81.8. Yield for the high-producing cows is assumed to be 97 lbs/cow, which is the sample average for multiparous cows early in their cycle. The percentage increase from changing calving timing is the difference in impact between multiparous cows early in their cycle and cows late in their cycle.

able to become pregnant costs the dairy operation $2.50 per cow due to lost production in the next production cycle [St-Pierre et al., 2003]. Finally, heat stress also weakens a dairy cow's immune system and makes them more vulnerable to disease and early mortality [Bagath et al., 2019, Bishop-Williams et al., 2015].

Dairy producers have options to mitigate heat stress by changing day-to-day production practices, investing in cooling systems, and changing the timing of breeding decisions. Within a cow's production cycle, farms can change the timing of feeding and rest to avoid additional movement or metabolic processing at the warmest parts of the day. Farms can also make capital investments into shade, fans, and sprinklers that cool cattle down during heat waves [Key et al., 2014, Armstrong, 1994]. These capital investments vary in their cost-effectiveness. Using a simulation model, St-Pierre et al. [2003] calculates that optimum heat abatement could reduce heat stress costs from all livestock industries by about $700 million. However, Gunn et al. [2019] finds that heat abatement is only cost-effective in the most intense heat waves. An arguably less-costly heat abatement strategy for some producers is to change the timing of their management decisions. Skidmore [2022] finds that Brazilian cattle ranchers sell cattle early to avoid having to raise cattle during the dry season. Even more relevant to the dairy industry is Ferreira et al. [2016] which uses a simulation model to show that cows about to give birth are the most vulnerable to heat stress. This suggests that changing the timing of when cows give birth is another way for dairy farms to mitigate heat stress.

A number of studies have attempted to quantify the impacts of heat stress on the dairy industry using small-sample on-farm data or aggregated, state-level data. Mukherjee et al. [2013], Qi et al. [2015], and Key et al. [2014] use stochastic frontier analysis to examine the impact of THI on the efficiency frontier of dairy farms throughout the country. In 100 farms in Florida and Georgia, higher THI was associated with less efficiency and investments in cooling systems were associated with higher efficiency [Mukherjee et al., 2013]. Key et al. [2014] is the most expansive study, using data from the Agricultural Resource Management Survey (ARMS) from 2005 and 2010, and finds a similar, negative relationship between THI and dairy farm efficiency. Njuki et al. [2020] uses a sample of Wisconsin dairy farms and calculates that the cost of heat abatement depresses productivity growth in dairy by about 0.3%. In terms of adaptation, Gisbert-Queral et al. [2021] uses state-level data in the US from 1981 to 2018 and finds that sensitivity to extreme THI was lower in 2018 than in 1981, supporting the idea that the dairy industry has adapted to extreme climate shocks over the past few decades. Gisbert-Queral et al. [2021] also finds an impact of extreme cold, though other studies find a small impact or no impact of extreme cold on milk production due to dairy cattle being resilient to temperatures as low as 0 degrees Celsius [Young, 1981, Lopez et al., 2022, Qi et al., 2015] Nevertheless, extreme cold can have negative impacts on the dairy operation beyond daily milk yield. Calves are vulnerable to cold after they are born and dairy farms may have to divert resources towards heating calf areas in particular during extreme cold [Roland et al., 2016].[1]

Our work makes two contributions. First, our work uses observational animal-level data, which can estimate a far more precise heat-stress impact than previous studies using farm- and state-level data. Vulnerability to heat stress depends on where a cow is in its production cycle, and the calculated impacts of heat stress can depend greatly on when observations are taken [Ferreira et al., 2016]. The majority of studies have annual data on milk production and have to make assumptions about how a year's exposure to heat

---

[1] We return to the question of the impact of low temperatures on milk yield in Appendix Appendix E.1

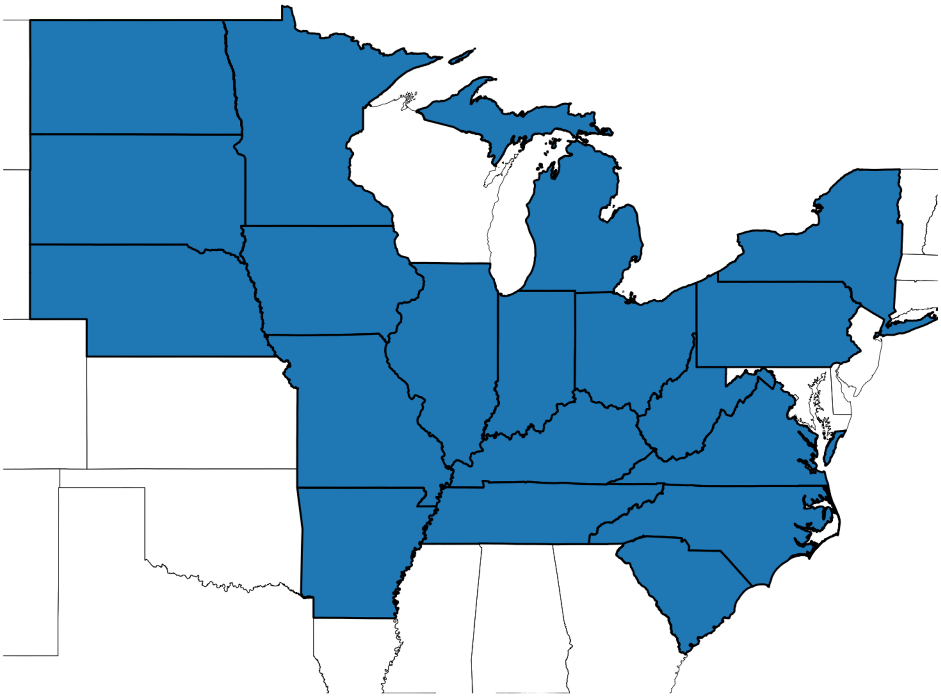


Figure B1: States with representative data in DRMS

will translate into the sum of production for that year. Having a single-day reading of the cow's production every month allows us to bypass these assumptions by estimating the heat stress impacts for different cohorts of cattle. Our second contribution is that we can examine how calving patterns impact heat stress. A straightforward way for dairy farms to mitigate heat stress is by changing the timing of their breeding decisions so that cows do not experience during their most vulnerable periods, specifically the first 120 days of their lactation. Previous studies have focused only on capital investments and have overlooked how breeding decisions may affect the impact of heat stress.

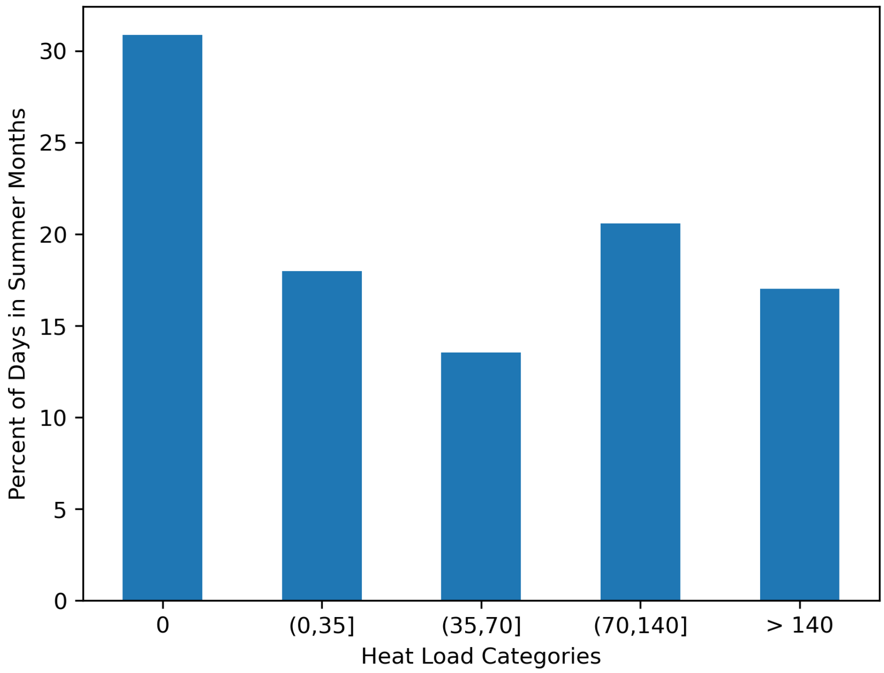
Appendix B Additional methods

Appendix B.1 Additional text and figures

Appendix B.2 THI heat load calculation

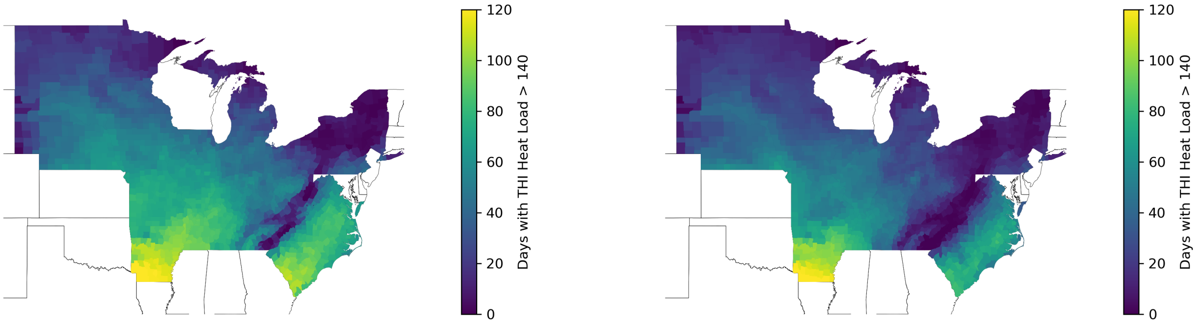
Heat load is calculated using the daily min and max of THI and modeling changes in THI throughout the day with a sine curve (see Figure B6 for a visual depiction). THI heat load

Figure B2: Heat load distribution in summer months

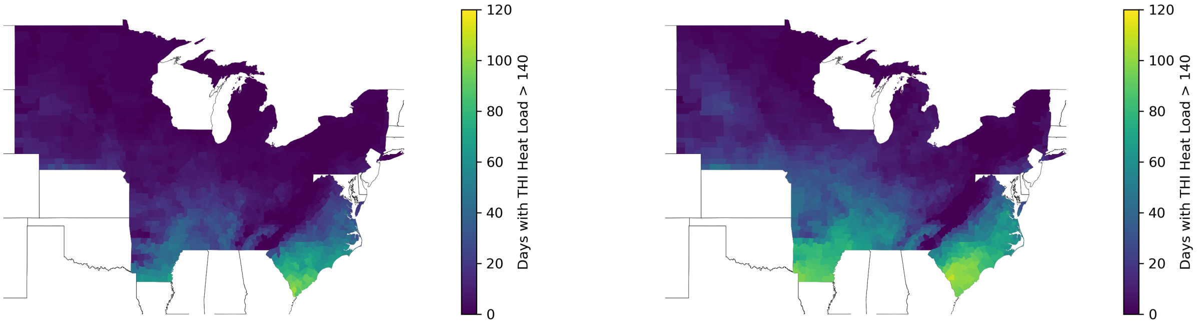


measures the area under the sine curve but above the THI threshhold, which increases when both THI min and max increase. This measure is often used in the literature to account for days where there is a lower THI max but still prolonged exposure to heat because of a high THI min. Heat load measures the amount of time that cattle spend above their critical THI threshhold which we consider to be 72 [St-Pierre et al., 2003]. Figure B6 is from Key et al. [2014] and shows that heat load is equivalent to the area under a sine curve fit using the THI min and max. Our heat load measure was calculated using the formula in the Appendix of St-Pierre et al. [2003] the THI min and max using this Python script:

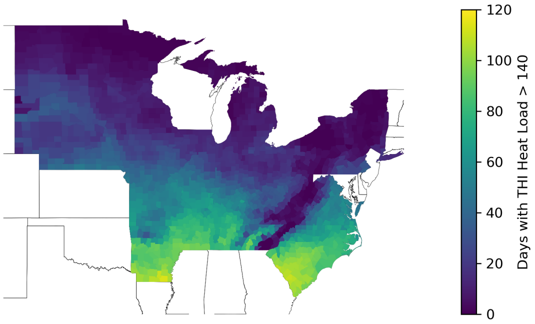
```
import numpy as np
P = 24
PI = np.pi

def heat_load(THI_min,THI_max,thresh):
    if thresh>=THI_max:
        res = 0
    else:
        THImean = (THI_max + THI_min)/2
        if thresh<THI_min:
            res = P*(THImean - thresh)
        else:
            amp = (THI_max-THI_min)/2
            if thresh>=THImean:
                x1 = np.arcsin((thresh-THImean)/amp)
```



(a) 2012 (b) 2013



(c) 2014 (d) 2015



(e) 2016

Figure B3: Total extreme heat load (> 140) days per county per year, 2012 - 2016

Figure B4: Lactation curve and the Wood model

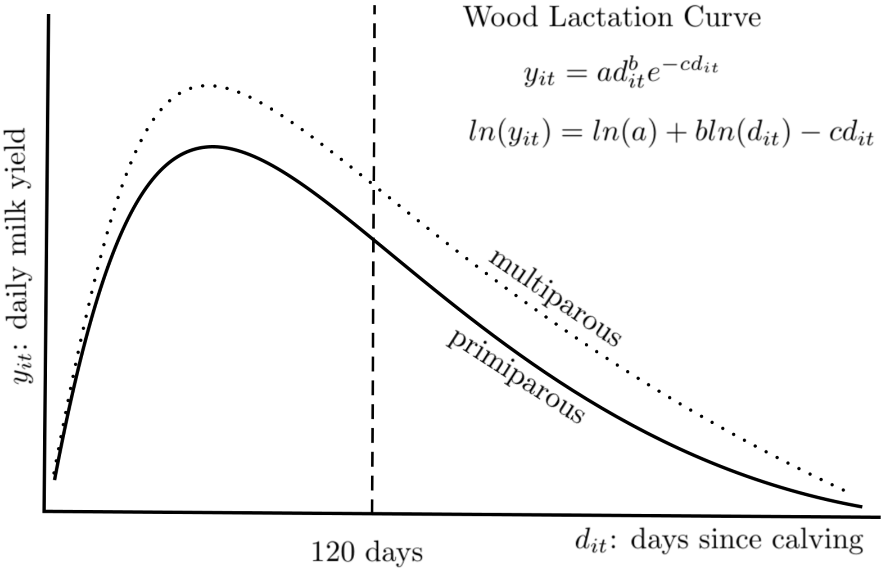


Figure B5: Leads and Lags of Heat Stress

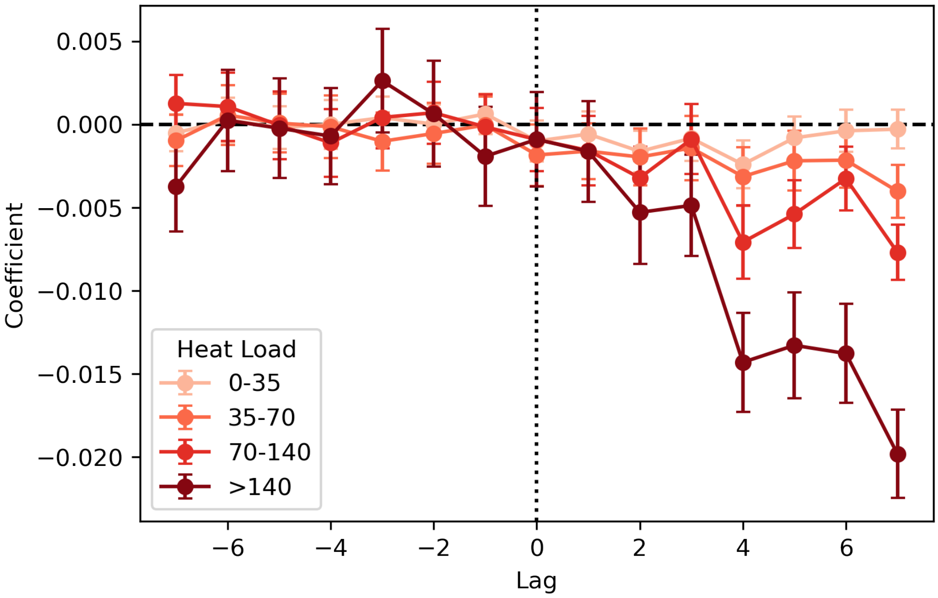
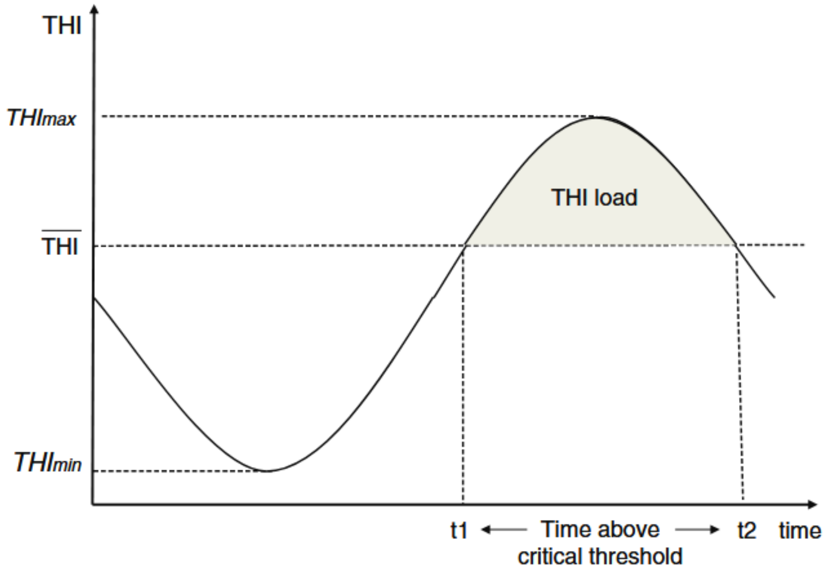


Figure B6: THI Load Model



Source: Key et. al. (2014)

```
            x2 = PI - x1
            res = (np.cos(x1)-np.cos(x2))*amp*P/2/PI - (x2-x1)*P/2/PI*(thresh-THImean)
        else:
            x1 = PI
            x2 = PI + np.arcsin((THImean-thresh)/amp)
            X = (np.cos(x2)-np.cos(x1))*amp*P/PI
            res = amp*P/PI + (THImean-thresh)*P/2 + (THImean-thresh)*((x2-PI)*P/PI) - X
    return res
```

Heat load is increasing in both THI max and THI min since they both increase the amount of exposure to heat. Figure B7 shows the relationship between THI max, THI min, and heat load. The common categories of low, moderate, and extreme stress days can roughly translate to different tiers of heat load. Low stress days with THI between 72 and 80 roughly translate to days where THI heat load is more than 0 and less than 70. Medium stress days with THI between 80 and 90 roughly translate to days where THI heat load is between 70 and 140. Finally, extreme stress days with THI above 90 usually have a heat load of at least 140.

Appendix C Tables

Appendix D State-level coefficients

Table C1: Effects of THI heat load, average and by lactation phase

	Ln(Milk Yield)
	Average
0-35	-0.002^{***} (0.001)
35-70	-0.005^{***} (0.001)
70-140	-0.009^{***} (0.001)
> 140	-0.020^{***} (0.001)
Observations	56,629,430
Adj. R^2	0.409

	Heat stress	Heat stress x Early DIM	Heat stress x Multiparous	Heat stress x Multiparous × Early DIM
0-35	-0.004^{***} (0.001)	-0.011^{***} (0.001)	0.014^{***} (0.001)	-0.030^{***} (0.001)
35-70	-0.007^{***} (0.001)	-0.008^{***} (0.001)	0.013^{***} (0.001)	-0.037^{***} (0.001)
70-140	-0.012^{***} (0.001)	-0.004^{***} (0.001)	0.015^{***} (0.001)	-0.045^{***} (0.001)
> 140	-0.020^{***} (0.001)	0.002 (0.002)	0.011^{***} (0.001)	-0.056^{***} (0.002)
Observations	56,629,430			
Adj. R^2	0.409			

Significance:	*p<0.1; **p<0.05; ***p<0.01
Covariates:	days in milk, log(days in milk), multiparous, somatic cell count
Fixed effects:	herd, month, calving month, year

Table D2: State-level coefficients

	Heat Load				
	0-35	35-70	70-140	140-210	> 210
State Name					
Vulnerable					
South Carolina	-0.028	-0.040	-0.042	-0.051	-0.104
Arkansas	-0.016	-0.015	-0.044	-0.050	-0.043
North Dakota	-0.017	-0.023	-0.020	-0.047	-0.013
Illinois	-0.006	-0.012	-0.020	-0.027	-0.034
Missouri	-0.006	-0.011	-0.019	-0.021	-0.034
Low-Level Resilient					
North Carolina	0.001	-0.002	-0.008	-0.030	-0.035
Tennessee	-0.002	-0.018	-0.007	-0.022	-0.029
Iowa	-0.002	-0.005	-0.006	-0.020	-0.031
Kentucky	-0.001	-0.011	-0.009	-0.020	-0.033
Virginia	0.001	-0.002	-0.008	-0.018	-0.037
Michigan	-0.004	-0.006	-0.008	-0.012	-0.025
Minnesota	-0.000	-0.001	-0.007	-0.014	-0.021
South Dakota	-0.004	-0.009	-0.010	-0.004	-0.029
West Virginia	-0.002	-0.008	0.005	-0.025	-0.003
Nebraska	-0.001	-0.003	-0.007	-0.011	-0.011
Resilient					
New York	-0.002	-0.002	-0.005	-0.011	-0.004
Pennsylvania	-0.002	-0.008	-0.010	-0.009	-0.018
Indiana	-0.001	-0.006	-0.005	-0.008	-0.005
Ohio	-0.001	-0.001	-0.007	-0.010	0.001

Figure B7: THI max, min, and load

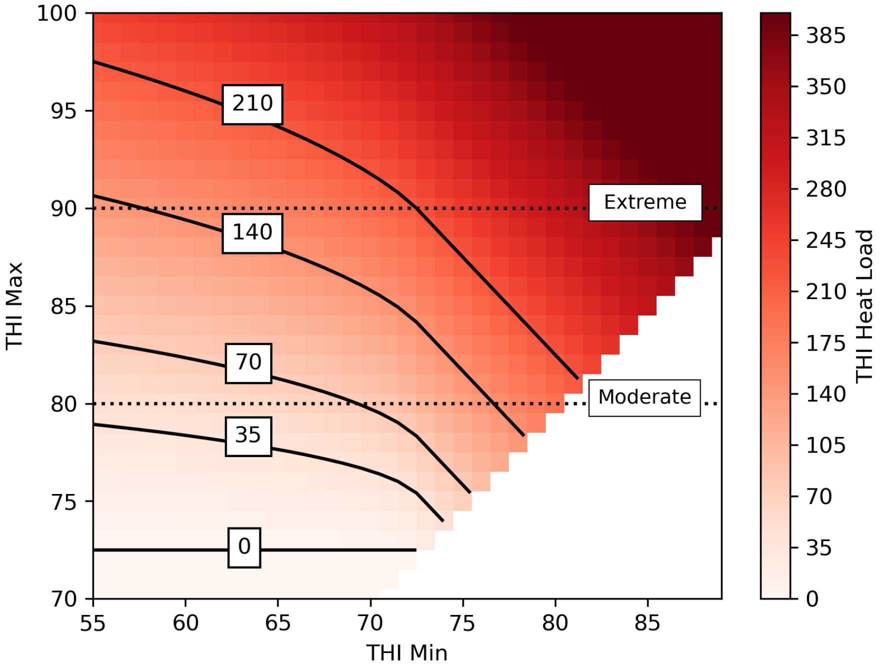


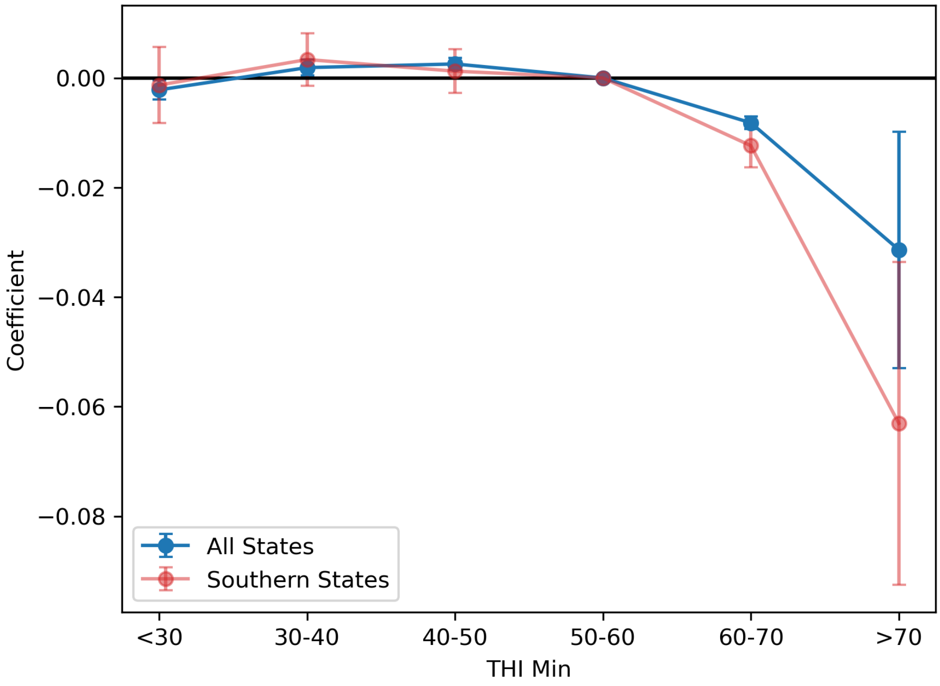
Table D3: State-Level Heterogeneous Coefficients pt. 1

		Heat Load	North Carolina	North Dakota	Ohio	Pennsylvania	South Carolina	South Dakota	Tennessee	Virginia	West Virginia
Primi	< 120 DIM	0-35	-0.004	-0.023	-0.018	-0.009	-0.057	-0.046	-0.007	-0.005	0.001
		35-70	0.012	-0.044	-0.018	-0.011	-0.083	-0.042	-0.003	-0.003	-0.006
		70-140	0.005	-0.011	-0.022	-0.013	-0.064	-0.045	-0.003	-0.004	0.023
		140-210	0.005	-0.016	-0.016	-0.009	-0.051	-0.039	-0.005	-0.010	-0.004
		> 210	-0.012	-0.004	-0.011	-0.013	-0.084	-0.054	-0.003	-0.024	-0.020
	> 120 DIM	0-35	-0.002	-0.021	-0.004	-0.001	-0.000	-0.008	-0.001	0.000	-0.005
		35-70	-0.008	-0.024	-0.003	-0.007	-0.026	-0.018	-0.016	-0.004	-0.004
		70-140	0.000	-0.031	-0.010	-0.008	-0.037	-0.009	-0.010	-0.011	0.018
		140-210	-0.015	-0.063	-0.013	-0.008	-0.045	-0.018	-0.021	-0.018	-0.026
		> 210	-0.011	0.004	0.010	-0.016	-0.100	-0.029	-0.024	-0.043	0.042
Multi	< 120 DIM	0-35	-0.012	-0.039	-0.035	-0.029	-0.068	-0.041	0.013	-0.013	-0.013
		35-70	-0.016	-0.056	-0.041	-0.040	-0.061	-0.046	-0.009	-0.022	-0.040
		70-140	-0.043	-0.013	-0.048	-0.047	-0.060	-0.051	-0.000	-0.028	-0.036
		140-210	-0.067	-0.090	-0.057	-0.048	-0.082	-0.052	-0.018	-0.053	-0.058
		> 210	-0.081	-0.063	-0.075	-0.064	-0.133	-0.086	-0.043	-0.067	-0.072
	> 120 DIM	0-35	0.012	-0.003	0.011	0.009	-0.021	-0.000	0.002	0.011	0.004
		35-70	0.004	0.006	0.013	0.005	-0.031	-0.007	-0.018	0.009	0.006
		70-140	-0.002	-0.029	0.009	0.005	-0.035	-0.012	0.000	0.002	0.011
		140-210	-0.034	-0.035	0.004	0.005	-0.047	0.011	-0.019	-0.003	-0.018
		> 210	-0.037	-0.004	0.026	-0.002	-0.105	-0.024	-0.024	-0.024	0.004

Table D4: State-Level Heterogeneous Coefficients pt. 2

			Arkansas	Illinois	Indiana	Iowa	Kentucky	Michigan	Minnesota	Missouri	Nebraska	New York
		Heat Load										
Primi	< 120 DIM	0-35	0.003	-0.016	-0.014	-0.011	0.007	-0.017	-0.022	-0.010	-0.008	-0.017
		35-70	-0.033	-0.037	-0.009	-0.020	0.012	-0.008	-0.021	-0.013	-0.013	-0.017
		70-140	-0.005	-0.024	-0.017	-0.018	0.010	-0.013	-0.020	-0.006	-0.012	-0.021
		140-210	-0.025	-0.031	-0.009	-0.025	-0.002	-0.010	-0.022	-0.011	-0.018	-0.021
		> 210	-0.016	-0.024	0.005	-0.034	-0.018	-0.019	-0.025	-0.017	0.000	-0.024
	> 120 DIM	0-35	-0.025	-0.003	-0.007	-0.003	0.006	-0.010	0.001	-0.007	-0.000	-0.006
		35-70	0.007	-0.016	-0.010	-0.003	-0.002	-0.006	0.001	-0.007	-0.018	-0.006
		70-140	-0.064	-0.022	-0.006	-0.006	-0.007	-0.017	-0.006	-0.017	-0.007	-0.009
		140-210	-0.028	-0.026	-0.018	-0.021	-0.014	-0.021	-0.009	-0.016	-0.019	-0.012
		> 210	-0.031	-0.036	-0.009	-0.034	-0.036	-0.028	-0.016	-0.030	-0.016	0.000
Multi	< 120 DIM	0-35	-0.011	-0.038	-0.019	-0.028	0.018	-0.038	-0.038	-0.003	-0.023	-0.040
		35-70	-0.016	-0.042	-0.023	-0.034	-0.010	-0.043	-0.040	-0.021	-0.024	-0.042
		70-140	-0.029	-0.055	-0.035	-0.039	-0.005	-0.049	-0.051	-0.032	-0.038	-0.045
		140-210	-0.070	-0.072	-0.035	-0.057	-0.028	-0.060	-0.062	-0.036	-0.037	-0.053
		> 210	0.005	-0.072	-0.039	-0.079	-0.029	-0.067	-0.070	-0.053	-0.041	-0.011
	> 120 DIM	0-35	-0.001	0.006	0.018	0.007	0.002	0.012	0.012	0.004	0.010	0.010
		35-70	-0.005	0.008	0.005	0.004	-0.006	0.002	0.011	0.000	0.020	0.010
		70-140	-0.034	-0.007	0.014	0.006	0.002	0.009	0.006	-0.009	0.009	0.007
		140-210	-0.045	-0.010	0.012	-0.008	-0.009	0.009	-0.002	-0.012	0.009	-0.002
		> 210	-0.054	-0.024	0.012	-0.011	-0.019	-0.016	-0.009	-0.025	0.003	-0.013

Figure E8: Cold and Heat Stress



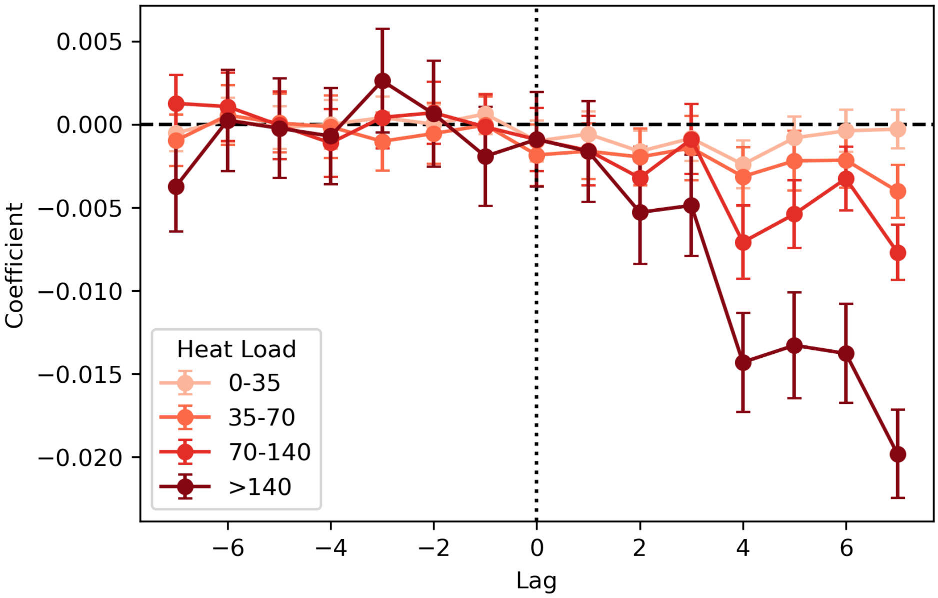
Appendix E Robustness Checks

Appendix E.1 Cold Stress

Dairy cattle are generally resilient to cold, even in some cases temperatures below 0 degrees Celsius [Kadzere et al., 2002, West et al., 2003]. Nevertheless, extreme cold can still impact the dairy operation by forcing farms to divert resources into taking care of calves that are at risk and low enough temperatures can impact cow milk yield. Using state-level milk production data, Gisbert-Queral et al. [2021] found evidence of milk yield declining when THI went below 60. Our data can be used to test how cold stress specifically impacts cow milk yield independent of other impacts on the operation.

Figure E8 shows the impact of minimum THI in contrast to the maximum THI measurement used to construct heat load. We look at both our whole sample, “All States,” and a sample of states with higher average temperatures where Gisbert-Queral et al. [2021] find the effects of cold stress to be highest, “Southern States.” Depending on humidity, a dry air temperature of 0 degrees C, sometimes considered the lowest critical temperature for a cow, maps to between 30 and 46 THI. Using 50-60 THI as a reference,

Figure E9: Leads and Lags of Heat Stress



we do not find minimum THI below 50 to have a significant impact on milk yield. However, when the minimum THI is above 60, we see a negative impact on milk yield. A minimum THI above 70 is especially impactful on milk yield because it does not allow dairy cattle to recover. With regards to cold stress, our results agree with other studies of cold stress and dairy production like Qi et al. [2015] and Lopez et al. [2022] which find little or no impact of cold stress on dairy production.

Appendix E.2 Leads and Lags of Heat Stress

A common assumption when studying the impact of an event is that the agents do not anticipate the event. If dairy farmers can anticipate the onset of heat, they take certain actions to mitigate its impacts. If this is the case, this changes the interpretation of the results and biases our estimates of the impact heat stress on milk yield. To test whether dairy farmers anticipate heat stress, we estimate the impact of both lags and leads of heat stress on milk yield. Figure E9 shows the impact of 6 days of both lags and leads. We find no consistent impact of leads on milk production at any level of heat stress, suggesting that dairy farmers do not appear to anticipate heat stress in a way that mitigates the impact of heat stress.