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

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Abstract

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. 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 2-5% of their milk production in a heat wave as opposed to at most 1% for other cattle. One low-cost form of adaption dairy farmers can use to mitigate these losses is changing the time of year that cattle can give birth. Using a back of the envelope calculation, we estimate that $950 million in lost profits could have been avoided in this period if all cows gave birth in the Fall instead of the Spring.

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1 Introduction

The dairy industry faces an impending challenge: increasingly frequent extreme heat events due to climate change (IPCC, 2022). Protecting livestock agriculture from the effects of climate change is a policy priority given that it is a high-value sector and contributes 40% of agricultural production in high-income countries and 20% in low-income countries (Food and Agriculture Organization of the United Nations, 2021). The dairy industry 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 in an extreme heat event (Key et al., 2014; St-Pierre et al., 2003; West et al., 2003).

The impacts of heat stress on dairy industry production has either been quantified using state-level data (Gisbert-Queral et al., 2021; St-Pierre et al., 2003) or using farm-level data from a limited number of herds (Bohmanova et al., 2007; Key et al., 2014). These types of data have two shortcomings. First, production data aggregated to the farm- or state-level hide an important determinant of heat stress: the timing of each cow's production cycle. Dairy cows will experience larger drops in milk production if they give birth in the Spring as opposed to the Fall because their most vulnerable period, right after they give birth, will coincide with the hottest part of the year. Dairy farms can decide to change when cows give birth to mitigate heat stress but this form of adaptation is not possible to detect when production data is aggregated. A second shortcoming of previous studies is that production data are almost always aggregated to the annual level. Without a daily measure of milk production, it is difficult to understand the precise impacts of heat waves on milk production.

Our research fills these gaps by studying the short-run impacts of heat stress and how patterns in calving dates mitigate the damages from heat stress. We pair a panel dataset of individual cow milk production collected every month for about 18,000 dairy farms throughout the Midwestern United States with daily temperature and humidity data. We find total losses for herds in our sample over the period are equivalent to 0.5% of the total dairy industry's profits in each year. In total, we estimate that the herds in our sample lost 418 million gallons of energy-adjusted milk and $2.87 billion in profit over five years due to heat stress. These losses were primarily due to medium-heat events where the temperature humidity index (THI) rose to between 80 and 90. Dairy cattle experience heat stress at THI levels of at least 72 THI (Armstrong, 1994). We find minimal losses due to low-stress events, despite evidence in the dairy science literature that even low-stress events affect milk yield. This suggests that farmers have already adopted methods to mitigate low-stress days.

Our novel data allows us to produce the first large-scale estimates of how the effects of heat stress vary 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, specifically cows that have given birth more than once and have given birth in the past four months. Cows with multiple births are the must vulnerable to heat stress in the first four months and experience a 2% drop in milk production when THI goes above 90. Three consecutive days of THI above 72 decreases their milk production by nearly 5%. In comparison, cows giving birth for the first time or that are in the last 6 months of their cycle experience at most a 1% drop in milk production from any heat event. We conclude by estimating the impact of a heat wave for each state individually and see evidence that states with more cows giving birth in the spring see larger heat stress impacts.

Our results have significant implications for understanding the impact of heat stress and adaption in the US dairy sector. First, the observed impacts of heat stress depend on where cows are in their production cycle. Because cows are most productive and vulnerable to heat stress early in their cycle, heat stress is less likely to appear significant in aggregated data if farms have already changed their calving dates. This leads to a second implication: farms can mitigate the economic damage from heat stress by simply changing the timing of their breeding decisions. Using our calculated heat stress impacts, we estimate a counterfactual where all cows that were early in their cycle during the summer months (May to August) were instead moved to a calving cycle that avoided these months (e.g., September or October). We estimate that $950 million worth of lost profit, about 33% of the total damages, could be avoided if older cows gave birth in the fall instead of the spring.

2 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 dropped about 1%. Heat stress also impairs the reproductive ability of cattle and makes it more difficult for cows to become pregnant (Jordan, 2003). Each additional day a cow is not 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 conditions within a cow's cycle, 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 used a simulation model to show that dry cows are even more adversely impacted by 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 some on-farm data and 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.

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). We also have measures of one-day milk yield, measured monthly, and daily data on heat events so we can understand the precise impact of a heat stress event when it happens. The majority of studies have annual data on milk production and have to make assumptions about how a year's exposure to heat will translate into the sum of production for that year. Having an actual 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

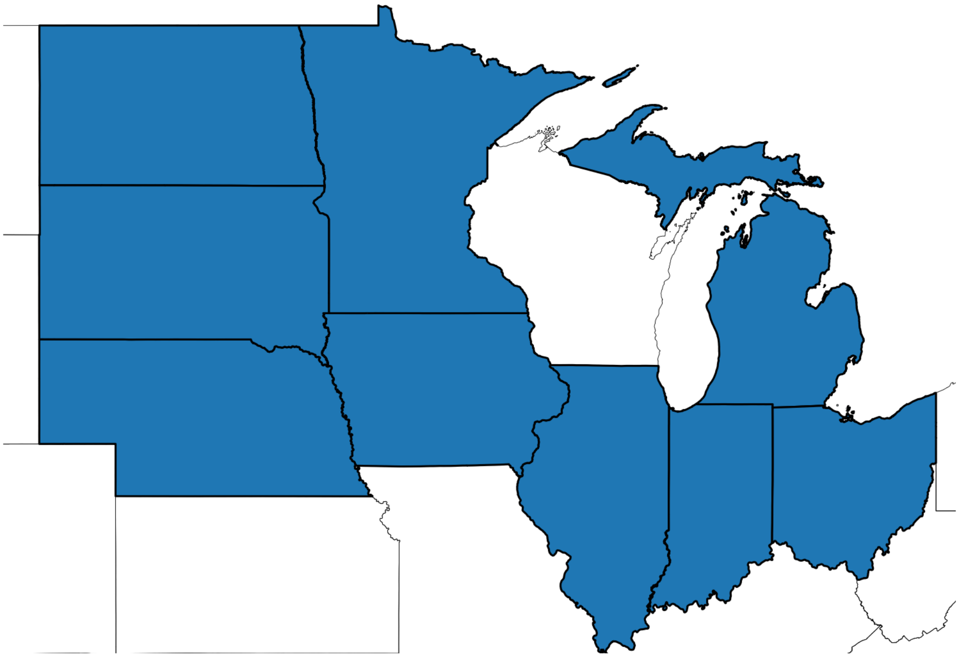


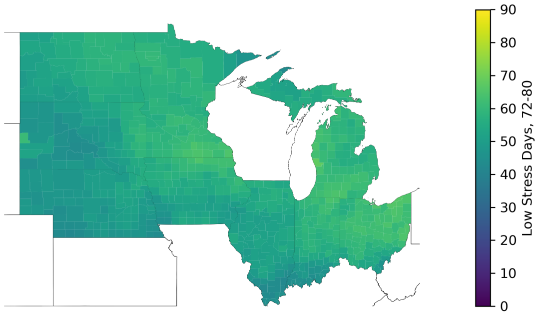
Figure 1: States with representative data in DRMS

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 changing breeding decisions as a cheap and effective method of adaptation.

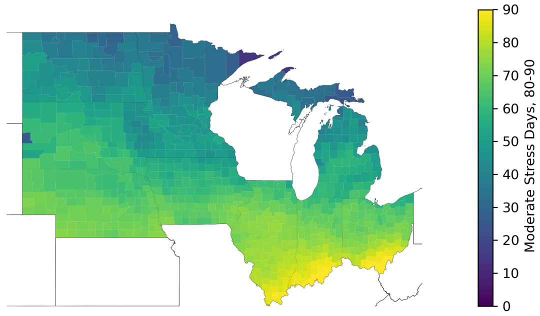
3 Data and Methods

3.1 Data

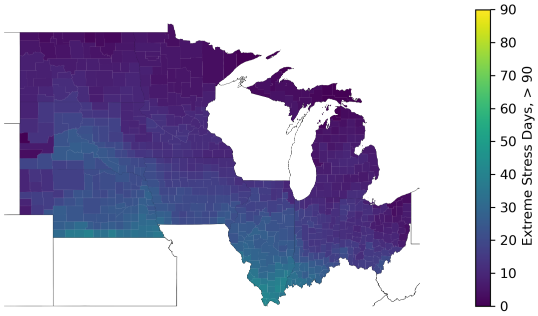
Dairy production data comes from Dairy Records Management Systems (DRMS), which samples and tracks dairy production on herds that are members of a dairy herd improvement association (DHIA). We use 120 million dairy cow production records sourced from over 18 thousand dairy farms from the years 2012 to 2016. Each farm's cows are sampled monthly, so the data are a panel of daily cow-level production for each farm that is a member of a dairy herd improvement association (DHIA). Our sample for this analysis cover the states in Figure 1. About 44% of dairy farms nationwide are members of DHIAs and in our chosen states, the Corn Belt and Upper Midwest, DHIA participation is usually about 50% (Council on Dairy Cattle Breeding, 2023). This sample also allows for a more comparable production system across states, as the states in this region have similar sized dairy farms and similar climates.



(a) Average low stress days per year



(b) Average medium stress days per year



(c) Average extreme stress days per year

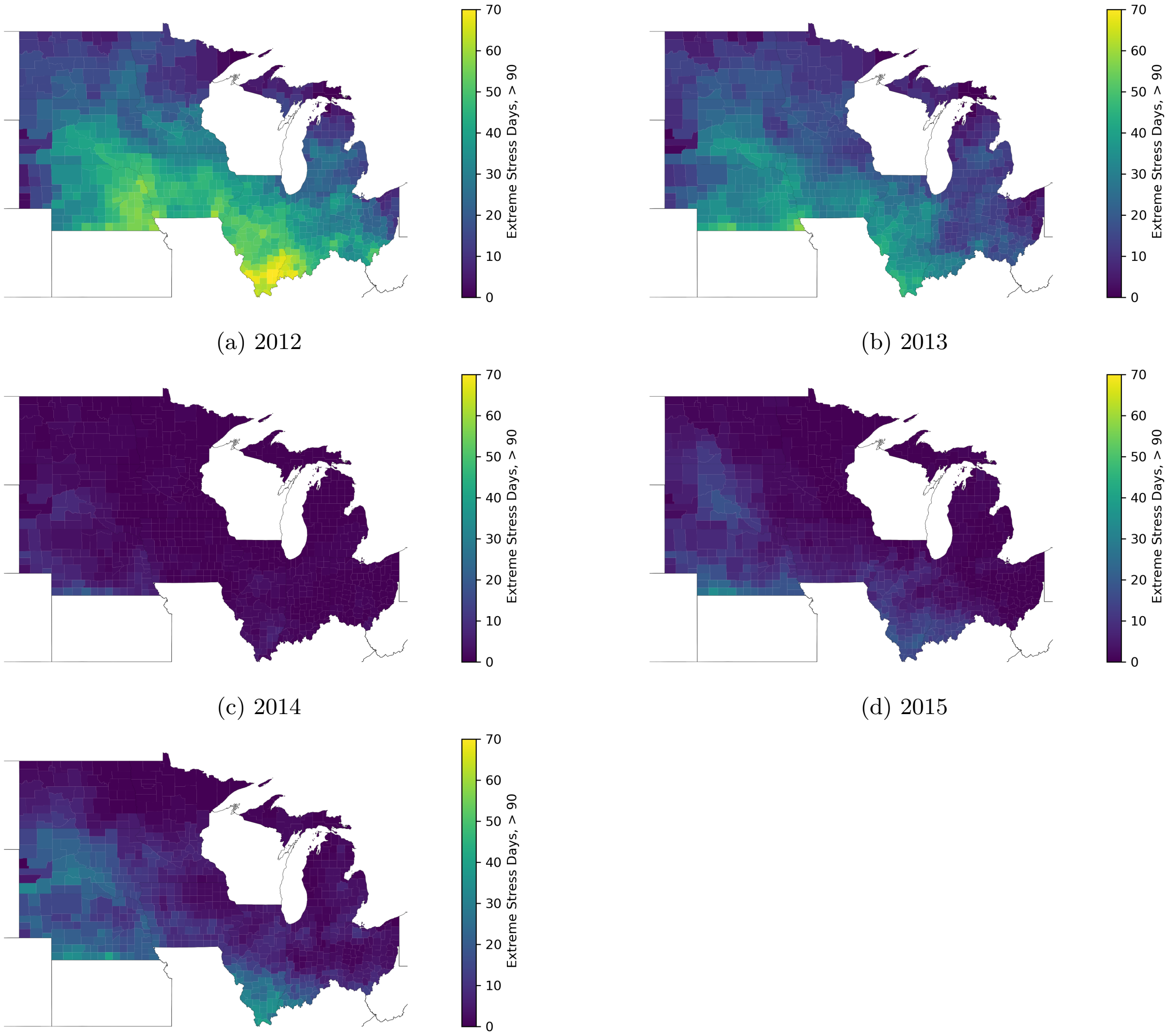
Figure 2: Average stress days per year by county and three levels of stress, 2012 - 2016

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. THI has been shown to be 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).[1] Figure 2 maps the average number of stress days per year in a given county over the period. Following Armstrong (1994), we use three categories of heat stress: low stress (72 - 79 THI), medium stress (80 - 89 THI), and extreme stress (greater than 90 THI). Heat stress follows expected geographical patterns, as more southern counties experience more days above THI stress thresholds. Figure 3 maps the average number of extreme stress days in a county each year over the period. The year 2012 is the hottest year in our sample; many counties experienced 50 or more extreme heat days in the summer. The following year was still very warm, while 2014 - 2016 were comparatively mild.

3.2 Empirical Strategy

Our goal is to estimate the impact of heat stress days on the daily milk production of individual cattle. A cow's production on a given day is not only explained by management and inputs but also by where

[1]We use the formula for THI from Mader et al. (2006) which is $THI = .8T + RH \times (T - 14.3) + 46.4$ where T is air temperature in celsius and RH is relative humidity which is between 0 and 1.



(a) 2012

(b) 2013

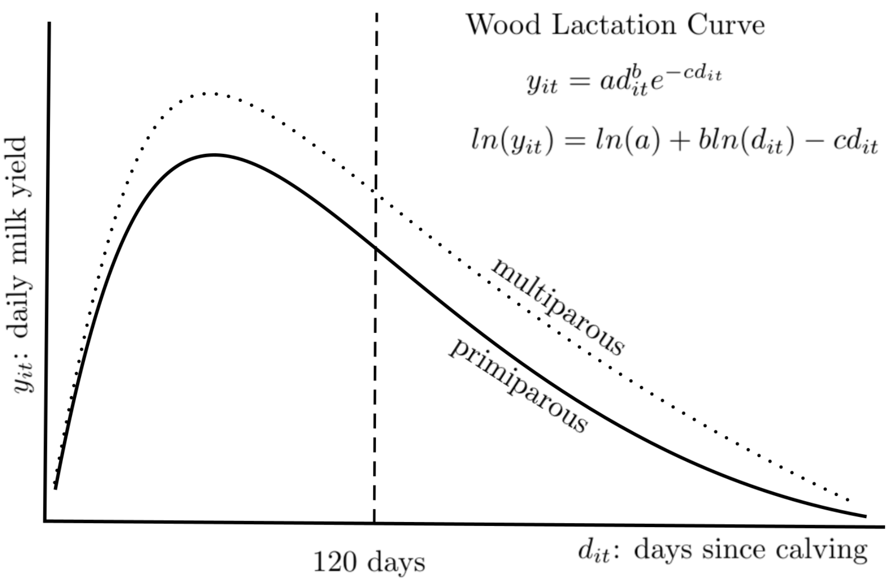
(c) 2014

(d) 2015

(e) 2016

Figure 3: Total extreme stress days per county per year, 2012 - 2016

Figure 4: Lactation curve and the Wood model



the cow is in its production cycle. The relationship of daily milk production to the days since the cow gave birth (called "days in milk" or DIM) is called the "lactation curve." Figure 4 shows the shape of the lactation curve, usually modeled mathematically as a half-gamma curve: $y = ad^{b}e^{-cd}$, where y is daily milk production, d is days since calving, and a, b, and c are parameters of the curve. By taking the natural logarithm of both sides, the log of milk production is linear in d and $ln(d)$: $ln(y) = a + bln(d) - cd$. This model is referred to as the "Wood model" (Wood, 1967).

Milk production reaches its peak in the first 120 days of a cow's production cycle. Milk production is also higher at every point for cows that have given birth multiple times, or "multiparous" (as opposed to primiparous cows that have only given birth once). To explore the heterogeneous impacts of heat stress, we consider four categories: primiparous cows before 120 days, primiparous cows after 120 days, multiparous cows before 120 days, and multiparous cows after 120 days. We expect that multiparous cows before 120 days will be the most vulnerable to heat stress are these cattle are devoting the most energy into milk production.

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. To estimate the average impacts of heat stress across all cattle, we use the following specification:

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

Our outcome, $ln(y_{ihct})$ measures the log milk production for cow i in herd h and county c at time t. We include the main factors from the Wood model interacted with the number of production cycles the cow has been through: $f(d_{ihct}, l_{ihct}) = l_{it} + bln(d_{it}) - cd_{it}$ where d_{it} is days in milk and 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). Our treatment is a series of dummy variables, $z_{c,t-k}$. Each dummy represents a range of values of THI, which we bin into low stress (72 - 79 THI), medium stress (80 - 89 THI), and extreme stress (greater than 90 THI). 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, as we anticipate that the effect of heat stress on production varies at the herd level with management practices.

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

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

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. The purpose of this specification is to determine the extent to which calving decisions determine the costs of heat stress. If there are no differences between these cohorts of cattle, then changing the timing of calving is not an effective method of mitigating heat stress. If significant differences exist, this would illustrate that producers can use calving decisions to buffer against heat stress.

4 Results

4.1 Heat Stress Impacts

We first estimate the average cost of heat stress across all cows in our sample. These results are similar to previous results in the literature, as they do not account for heterogeneous effects based on the cow's characteristics or regional (i.e., sub-state) climate. Concurring with the literature, we find that milk yield falls due to heat stress and the effects persist or even increase beyond the day of the heat event. The top of Table 1 shows the average effect of three mutually exclusive stress categories. We do not find a significant average yield loss due to low (i.e., 72 - 79 THI) stress on the day of or day after event, but we find a 0.4% yield loss two days after a low-stress event. We find contemporaneous, one- and two-day lagged losses due to medium (i.e., 80 - 89 THI) of 0.3%, 0.4% and 0.9%, respectively. For extreme (i.e., greater than 90 THI) stress, we find 0.8%, 1.1% and 1.8% contemporaneous, one-, and two-day lagged losses. While the impacts of heat stress should be felt by cattle above 72 THI, the lack of effects here seems to indicate that farms in this sample have the capacity to shield cattle from a low level of heat stress.

At the bottom of Table 1, we estimate the effects for the week after the event. We find 0.2 - 0.3% losses two, four, and six days after a low-stress event. Medium stress events reduce milk yield by 0.2 - 1% all days after the event, while extreme stress events reduce milk yield by 0.5 - 2.9% following the event on all days except the second. For medium and extreme stress events, the effects peak at the end of the included lags (i.e., the sixth lag). The increasing effects over time that we estimate here may indicate non-linear effects of repeated stress events during a heat wave. While we control for all lagged stress levels independently, we do not capture non-linear cumulative effects in this model.

Table 1: Effects of three distinct heat stress categories on log milk yield

	Ln(Milk Yield)						
	Lag = 0	Lag = 1	Lag = 2				
Low stress	−0.001	−0.0005	−0.004***				
	(0.001)	(0.001)	(0.001)				
Med stress	−0.003**	−0.004***	−0.009***				
	(0.001)	(0.001)	(0.001)				
Ext stress	−0.008***	−0.011***	−0.018***				
	(0.002)	(0.003)	(0.002)				
Observations	26,047,050						
Adj. R^2	0.382						
	Lag = 0	Lag = 1	Lag = 2	Lag = 3	Lag = 4	Lag = 5	Lag = 6
Low stress	−0.001	−0.001	−0.003***	−0.0004	−0.003***	0.002	−0.002**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Med stress	−0.0004	−0.002*	−0.004***	−0.003**	−0.007***	−0.003**	−0.010***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Ext stress	−0.002	−0.005**	−0.003	−0.006**	−0.012***	−0.016***	−0.029***
	(0.002)	(0.003)	(0.003)	(0.002)	(0.002)	(0.003)	(0.003)
Observations	25,987,235						
Adj. R^2	0.382						
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						

Next, we examine the impacts of heat stress on different cohorts of dairy cattle. Figure 5 shows the impacts of a single low, medium, and extreme heat stress day on milk production. 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. A multiparous cow that is early DIM produces experiences a 1% yield loss due to low stress, a 1.1% loss due to medium stress, and a 2.2% loss due to extreme stress. In comparison, primiparous cows early in their cycle see no statistically significant impact of heat stress.

Cows also experience significant losses in the phase immediately preceding this: the end of the first lactation cycle. The primiparous cows late in their cycle lose 0.6% due to medium stress and 1.4% due to

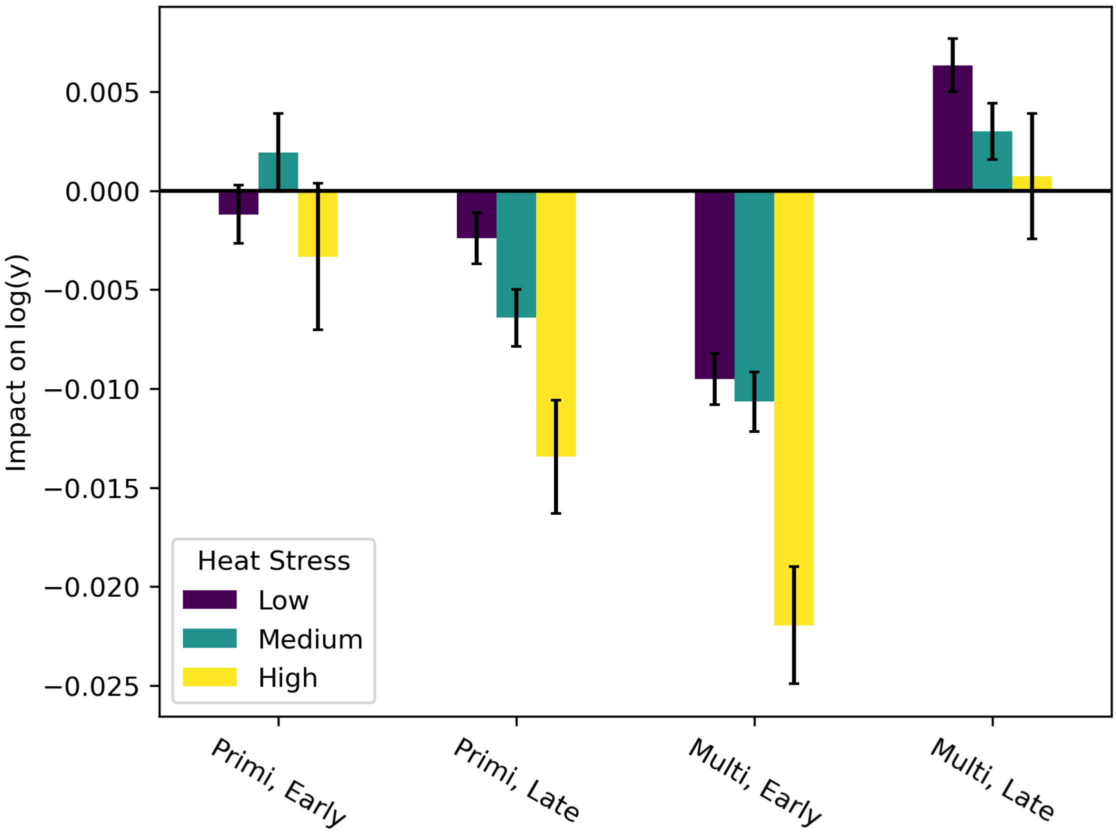


Figure 5: Effect of day-of heat on milk yield

extreme stress, respectively. There are two potential explanations for why cows experience losses during this phase. First, this second calving cycle is physically precarious, as the animal is transitioning from heifer to cow. Second, given the semi-seasonal patterns of calving cycles primiparous cows in our data, many of the primiparous cows that are exposed to heat stress late in their cycle are being exposed to experience extreme heat for the first time while milking. This first exposure is likely to stimulate the largest biological response.

We next consider the impacts of consecutive stress days in Table 2. Here, we consider the effect of any stress days over 72 THI, as separating the categories would undermine our ability to identify consecutive stress days in separate categories. In the first part of the table, we quantify the average effects over all cows. We estimate a 0.2% loss following one stress day in the previous three, a 0.3% loss following two stress days, and a 1.0% loss following three consecutive stress days. This is indicative of the non-linear losses following consecutive days. While the losses following one or two stress day are similar to our estimates of the contemporaneous effect of a medium stress event, the losses following three consecutive days of any stress are similar to the losses from a single day of extreme stress.

Table 2: Effects of consecutive days over THI, average and by lactation phase

	Ln(Milk Yield)			
	Average			
One stress day	-0.002^{*}			
	(0.001)			
Two stress days	-0.003^{**}			
	(0.001)			
Three stress days	-0.010^{***}			
	(0.001)			
Observations	26,047,050			
Adj. R^2	0.381			
	Base	Multiparous	Early DIM	Multiparous × Early DIM
One stress day	-0.004^{***}	0.011^{***}	-0.0002	-0.021^{***}
	(0.001)	(0.001)	(0.002)	(0.002)
Two stress days	-0.005^{***}	0.015^{***}	0.0001	-0.029^{***}
	(0.001)	(0.001)	(0.002)	(0.002)
Three stress days	-0.013^{***}	0.018^{***}	0.008^{***}	-0.047^{***}
	(0.001)	(0.001)	(0.001)	(0.001)
Observations	26,047,050			
Adj. R^2	0.382			
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			

In Figure 6 and the bottom of Table 2 we quantify the effects of multiple heat stress days on different

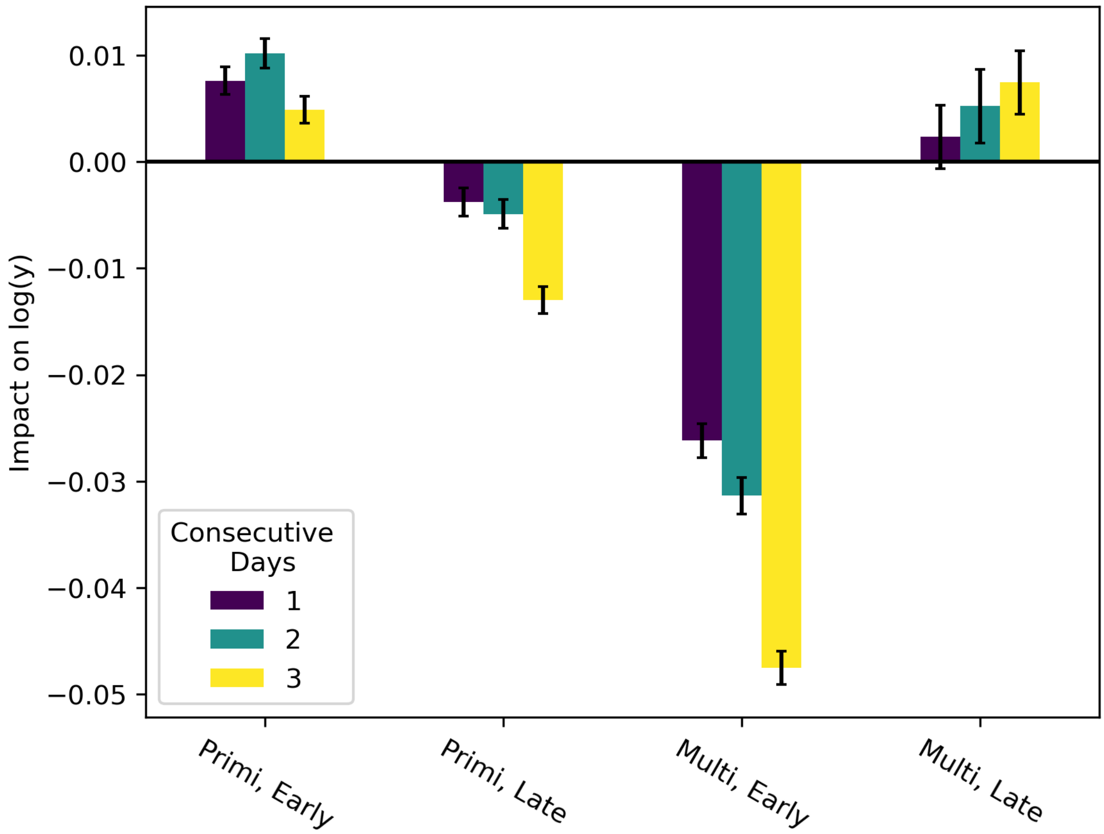


Figure 6: Effect of up to three consecutive heat days on yield by phase in cow's lactation cycle

cohorts of cattle. Again, we see that heat stress losses are worst for cows early in their cycle after multiple births ("Multi, Early"). A multiparous cow that is early DIM produces 1.4% less following heat stress on one of the previous three days, 1.9% less following stress on two of the previous three days, and about 5% following three consecutive days of heat stress. Primiparous cows that are late in their cycle experience 0.4, 0.5, and 1.3% losses following one, two and three days of heat stress, respectively. Other cohorts of cattle do not experience significant changes in milk production. Our results suggest that the impacts of heat stress found in larger, more aggregated data are likely almost entirely driven by dairy cows in this phase of their cycle.

4.2 Cost Calculations

We use these estimates to calculate the total cost of heat stress for a hundred-cow herd in our sample. The average county in our sample experienced 315 low-stress, 298 medium-stress, and 64 extreme-stress days over the five-year period. For a hundred-cow herd with an average yield of 80 pounds of energy-adjusted milk per cow, this is equivalent to 17,671 pounds of milk lost due to low-stress days, 64,369 pounds lost due to medium-stress days, and 34,626 pounds lost due to extreme stress. In total, a hundred-cow herd under the average weather conditions in our sample lost 116,666 pounds of energy-adjusted milk to heat stress over five years. At $10 profit per pound of milk, this is equivalent to $1.2 million dollars in lost profit.[2]

Next, we estimate a back of the envelope calculation of the total yield loss in our sample over the five year period. In each county and each month, we estimate the total milking herd in the county and multiply this by an average winter yield of 80 pounds of milk per cow per day. This calculates a rough total county-level counterfactual yield. We multiply this yield by the total number of heat stress days in the county and the total yield lost due to that category of heat stress. We then multiply this loss, in pounds of milk, by the profit margin of milk in that month. Across all of the herds in our sample, we estimate a total loss of 418 million gallons of energy adjusted milk over the period. This is composed of 75 million lost due to low-stress days, 235 million lost due to medium-stress days, and 106 million lost due to extreme-stress days. At $10 profit margin per pound of milk, this is equivalent to $2.87 billion in lost profit over 5 years. While losses varied greatly year-to-year, this comes out to 574 million in lost revenue per year, on average. This is equivalent to 0.5% of the total profit of the dairy industry during this time period.

Under current climate conditions, the highest losses are due to medium-stress days. This is due to their combination of relatively high yield loss per cow and the frequency of these events. However, it

[2]In the period 2012 to 2016, the income over feed cost, a measure of the profit margin for dairy farms, was about $8.5 per pound of milk.

is important to note that 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.

How much of these losses are due to vulnerable cattle? We calculate the total seven-day losses following one day of low, medium, or extreme stress for a multiparous cow early and late in their lactation cycle. The week following a low-stress day, multiparous cows lose 3.7% of a day's yield early in their cycle and have no losses late in their cycle. Following a medium-stress day, they lose 5.8% early in their cycle compared to 2.6% late in their cycle. Following an extreme-stress day, they lose 12.4% early in their cycle, compared to 6.6% late in their cycle. We use these numbers to estimate the total losses of multiparous cows early in their cycle in May through August and find these losses account for \$1.32 billion of the \$2.87 billion lost profit (45%) in our sample.

Finally, how much loss could be averted if producers simply changed their calving dates? We estimate a back of the envelope estimate of the avoided losses if all of the multiparous cows in our sample had been more than 120 day post-birth during the summer months (May - August). This is equivalent to a regional herd with no calving from February to August. We find this adjustment would have mitigated \$0.95 billion in lost profit. This estimate does not include potential general-equilibrium effects of all herds shifting to a fall calving cycle. However, since the herds in our sample are primarily supplying milk for processed dairy products with a longer shelf life, we expect the general equilibrium effects to be minimal.

4.3 Heat Stress and Calving Patterns Across States

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. Since not all farms are equally exposed to heat stress, we would expect the impacts of heat stress to be different across the states in our sample. We finish our analysis by examining how heterogeneous the impacts of heat stress are across states and whether patterns in calving differ across states. If states with heat stress are shifting more calvings to the fall instead of the spring, this is evidence that calving patterns may be changing in reaction to heat stress.

In Figure 7, we map the three-day effect of extreme heat by state. We map losses over the three day period in terms of day-of, one-day-lagged, and two-day-lagged losses and discuss here the sum of these coefficients. The sum of these coefficients represents the total three-day losses as a percent of a single day's yield.

Herds in North Dakota are the most affected by heat stress. Following extreme heat, their total loss over three days is equivalent to 7.3% of a one-day yield. All other states experience 2 (Indiana, Ohio)

3 (Minnesota, South Dakota), 4 (Iowa, Michigan) or 5% (Illinois) losses over the three days following extreme heat. This high effect in North Dakota is not purely driven by a lack of extreme-heat events in our data; herds in North Dakota also lose 3.9% and 3.7% of a day's yield in the three days following low and medium stress, respectively. All other states lose 1 (South Dakota, Indiana, Michigan, Minnesota) or 2% (Iowa, Illinois, Ohio) following a medium stress event; only South Dakota experiences more than 1% loss following a low-stress event.

In Figure 8, we map the effect of experiencing one, two, or three days of stress (over 72 THI) in the previous three days. We again observe that North Dakota is the most impacted, with 2.7 and 3.3% losses after two and three heat days. Most other states have 1 - 2% losses after three heat days, although Indiana has no significant loss following three days of stress. While there may appear to be patterns of the magnitudes of effects based on average temperature, we detect no significant difference in the effects of heat stress based on the local climate. Table 3 tests for heterogeneous effects based on the average number of heat days in the county, defining a "hot climate" as a county which experiences more than 120 heat stress days on average in the year. There are not significant differences between the upper and lower half of the sample. These results are robust to alternative divisions of the sample. These results suggest that adaptation and mitigation requires more than simply exposure to heat stress. Future work should explore the factors driving this heterogeneous adaptation across climates and states.

4.4 Heat stress effects over a cow's production cycle

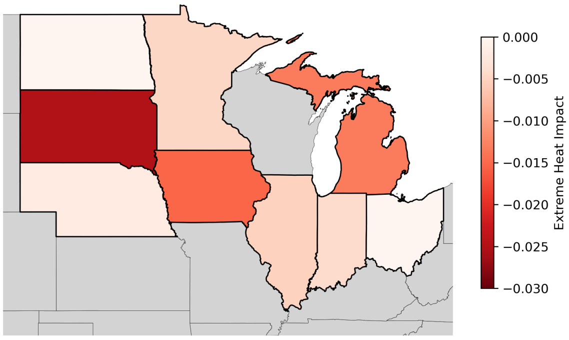
In Figures 9 and 10, we graph the distribution of calving months (i.e., how many cows give birth in each month) and average monthly temperature by state. We compare the percent of the herd that calves in a month to the percent that we would observe if calving were distributed randomly throughout the year: 8.3% per month.[3] The 8.3% per month rate is represented by the dashed, horizontal line.

We observe that disproportionately more cows give birth in fall months (i.e., after September) in states with more extreme summer temperatures. Illinois, Indiana, and Iowa all experience an average of 7.5 or more extreme stress days in July; they also calve at least 10% or more of the annual total in September and nearly that in October and November. These fall calvings replace calvings in March, April and May, all three of which fall below an 8.3% calving rate. We also observe more subtle versions of these patterns in Michigan, Minnesota, Ohio, all of which experience an average of 5 or fewer extreme heat days in August. These patterns suggest that some farmers are using the timing of calving to minimize losses from heat stress. These patterns may in part also be driven by lower conception rates during heat events. Given a cow's ten month gestation, this could drive lower calving rates in April and May. Notably, the

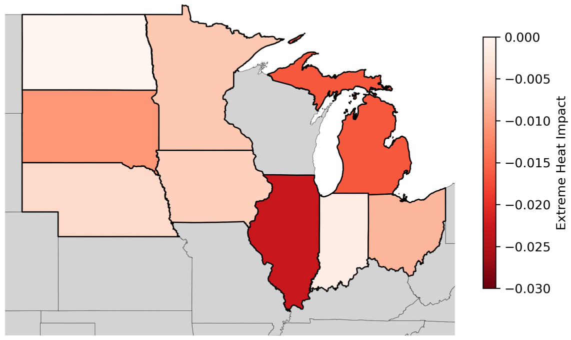
[3]We normalize the number of calvings per month to a 30-day month.

Table 3: Effect of heat stress on milk yield based on the average number of heat days in the county

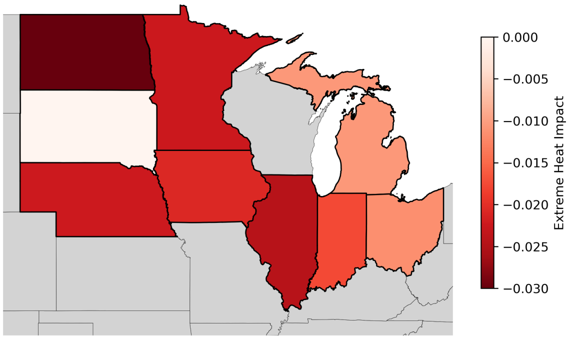
	Ln(Milk Yield)		
	Lag = 0	Lag = 1	Lag =2
Low stress	0.0002	−0.001	−0.004***
	(0.001)	(0.001)	(0.001)
Med stress	−0.002*	−0.002	−0.008***
	(0.001)	(0.002)	(0.002)
Ext stress	−0.009***	−0.007**	−0.019***
	(0.003)	(0.003)	(0.004)
Low stress × Hot climate	−0.001	0.001	0.0001
	(0.002)	(0.002)	(0.002)
Med stress × Hot climate	−0.0001	−0.003	−0.001
	(0.002)	(0.003)	(0.002)
Ext stress × Hot climate	0.001	−0.006	0.002
	(0.005)	(0.005)	(0.005)
Observations	26,047,050		
Adj. R^2	0.381		
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		
Note:	Hot climate = more than 125 days of heat stress on average a year.		



(a) Lag = 0



(b) Lag = 1

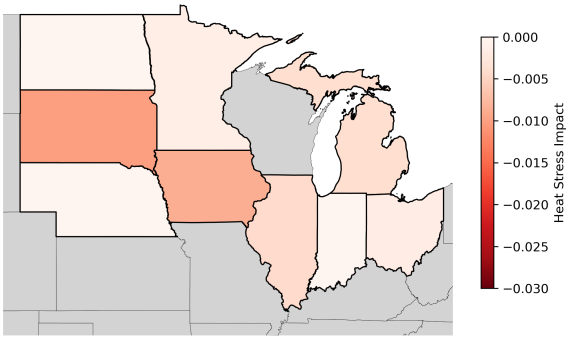


(c) Lag = 2

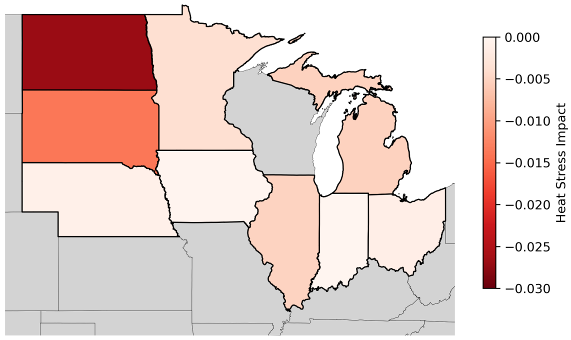
Figure 7: Three-day effect of extreme heat stress (over 90 THI) on milk yield by state

Dakotas, and particularly North Dakota, do not follow a clear seasonal pattern. South Dakota on average has more calves in the fall than the spring, but there is a small summer peak in calving. In North Dakota, there is no evidence of fall calving. Indeed, summer is the most common calving period in the state.

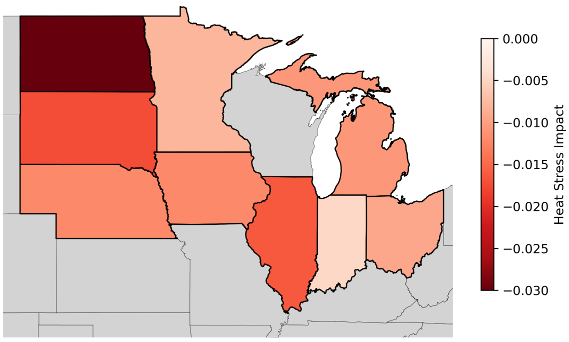
Seasonal calving patterns may also explain differences in average heat stress effect across states. In particular, it may explain the high vulnerability of the herds in North and South Dakota to heat stress, as they have relatively more calves early in their production cycle in the summer. As such, the average losses across their herds are higher relative to a state that has fall calving patterns. However, these patterns do not explain the entire variation in heat stress effects, nor does the average number of heat stress events predict county-level calving patterns. Further research should investigate the conditions under which a farm adopts seasonal calving as well as the other management practices that farmers adopt to mitigate heat stress.



(a) 1 day



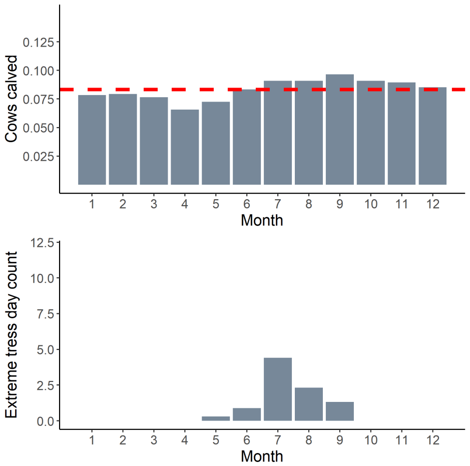
(b) 2 days



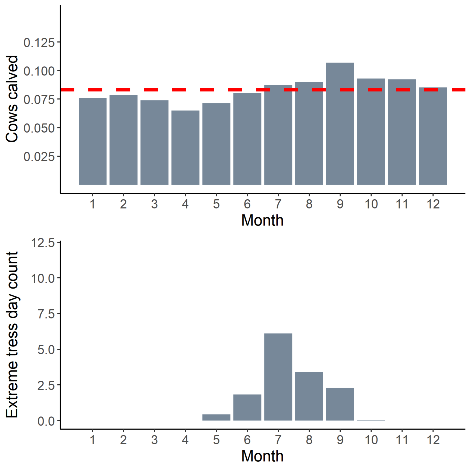
(c) 3 days

Figure 8: Effect of number of days of heat stress (over 72 THI) in the previous three days on milk yield by state

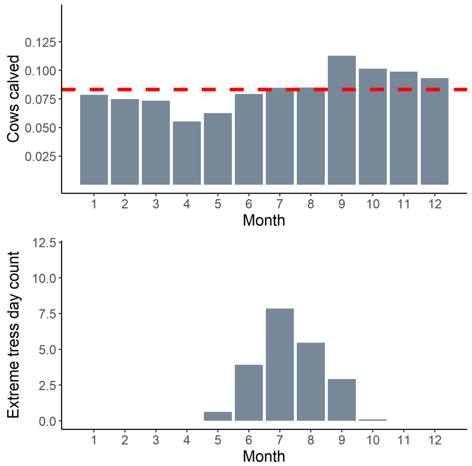
Figure 9: Calving Patterns and Average Heat Events in Select States



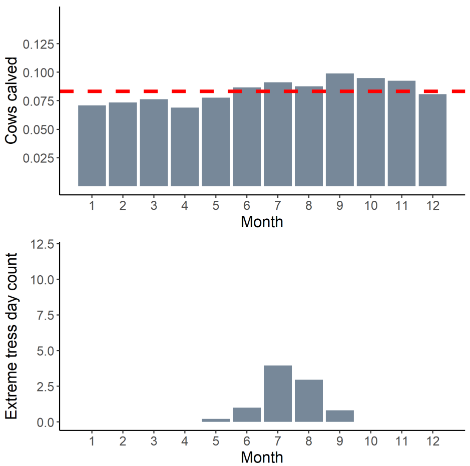
(a) Ohio



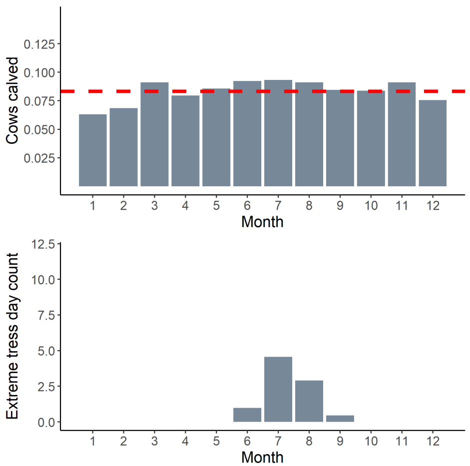
(b) Indiana



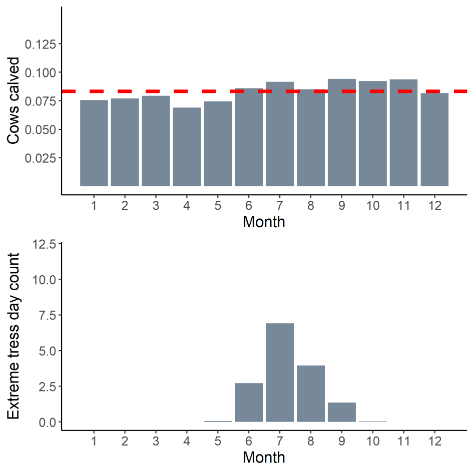
(c) Illinois



(d) Minnesota

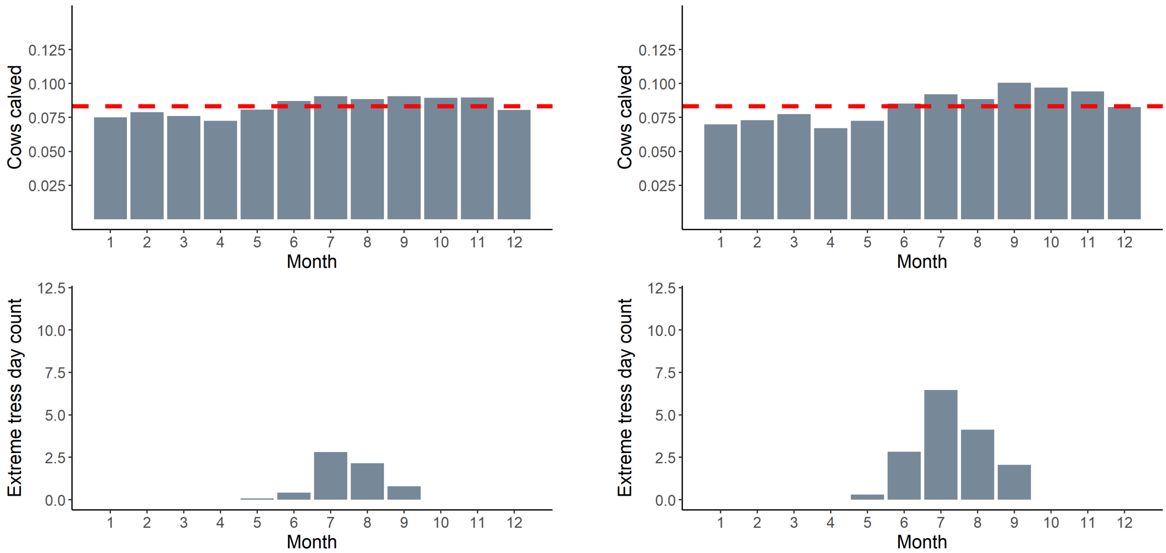


(e) North Dakota



(f) South Dakota

Figure 10: Calving Patterns and Average Heat Events in Select States, Continued



(a) Michigan (b) Iowa

5 Conclusion

Our analysis calculates the impacts of heat stress on the US dairy sector using animal-level data from the Midwest in the period 2012-2016. Our unique data allows us to understand how heat stress impacts different cohorts of dairy cattle across production cycles. We find that most of the heat stress impacts in our data are being driven by medium heat stress, that is days with a THI between 80 and 90, and cattle that are early in their production cycle and have given birth multiple times. For these cattle, the impact of extreme heat stress is about double compared to other cattle.

After conducting a back of the envelope calculation, we calculate that \$2.87 billion in dairy industry profits were lost in our five year period because of heat stress. Of this \$2.87 billion, a little less than half of this loss was from cattle who were exposed to heat stress during their most vulnerable and most productive months. We estimate that about one-third of this loss would be averted by dairy farmers simply changing their calving dates so that these vulnerable dairy cattle are less exposed to heat.

In terms of evidence of adaptation, we see very little impacts of low-stress days where THI is between 72 and 80 despite the fact that cattle should see decreased milk production when THI goes above 72. We do not find as large of impacts as previous studies, which suggests that some mitigation has likely taken place. With respect to calving dates, we see evidence that states with a large number of stress days have shifted calving dates to the fall instead of the spring. Some states with more spring calvings are also seeing larger heat stress impacts.

Our work demonstrates 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. 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 changes in calving dates to mitigate heat stress suggest there are still low-cost ways for livestock producers to buffer themselves from the harmful impacts of increasing heat.

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