Air Conditioning for Cows? Determining the Effects of Heat and Cold Stress on Dairy Cattle Using Applied Economics

by

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This project is dedicated to the family members who aren't here to see me succeed. I hope you are proud.

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ABSTRACT

This undergraduate honors thesis uses an ordinary least squares regression model to measure the relationship between temperature and milk output in the dairy industry followed by a partial equilibrium analysis to estimate the welfare impacts of increasing global temperatures. Regression results show that milk output is subject to both heat and cold stress and that there is an optimal temperature for dairy production. However, the average U.S. temperature is currently below the optimal threshold. Thus, rising average temperatures may increase the milk supply nominally as cows spend more time in the thermoneutral comfort zone. However, the increased farm revenue from increased production is offset by lower market prices, resulting in a small negative financial impact for dairy farmers and a $123.1 million increase in consumer surplus. Assuming a warmer base temperature, production would decrease, pushing prices up slightly while cutting $3 million in farm revenue and $50 million in consumer surplus.

Keywords: heat stress, cold stress, dairy cattle, applied welfare economics, partial equilibrium, elasticity of demand, climate change, agriculture

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I. INTRODUCTION

U.S. dairy farms drive a complex multiproduct industry that has a total economic impact of $752.9 billion annually. It is a massive industry that provides great economic and nutritional value. Nationally, it sustains over 3.3 million jobs and supports over $41 billion in direct wages (Dykes, 2021), which means that changes are likely to affect the livelihood of producers and downstream consumers worldwide. According to the Food and Agriculture Organization (IDF, 2013), milk represented 8.9% of the value of all agricultural products in 2010.

Dairy is a unique industry that is affected by countless variables. As an animal-based production system, output is affected by the laws of nature. This includes health, environment, time of year and the lactation cycle. Additionally, market conditions are affected by the product's highly perishable nature. As Zhang & Alston (2018) note, dairy is typically processed and sold through cooperatives that focus on minimizing costs and clearing all product rather than maximizing profits.

The industry is also tightly regulated through the Federal Milk Marketing Orders (AMS, 2019). This program determines who can handle milk for drinking or manufacturing. It establishes four classes of milk: Class I is for drinking, Class II is for yogurt, ice cream and soft cheese, Class III is used to make hard cheese, and Class IV is used to make butter and powdered dairy products. The marketing order system also establishes minimum sales prices and ensures that farmers receive pooled or averaged prices for their milk based on its total butterfat content.

Although these policies help to stabilize prices and ensure a more consistent milk supply, they may also prevent dairy from functioning like a true free-market commodity. While economists have invested considerable time into researching dairy consumption patterns among retail consumers, there has also been growing interest in determining how rising temperatures related to global warming are affecting the dairy industry. The physiological effects of heat stress on the dairy industry and agriculture in general are well established, but the economic effects are less certain.

The goal of this study is to quantify the economic losses that dairy farms experience due to heat stress. Specifically, we are measuring the relationship between temperature and milk output. A linear regression analysis allows us to determine how temperature affects milk production, which in turn affects the market supply. Because symptoms increase rapidly at elevated temperatures, we expect not only to be able to estimate the impact of a 1°F temperature change but also to observe a steeper trendline, indicating a stronger negative correlation, when temperature conditions are more extreme.

Heat Stress

Heat stress is a thermo-metabolic condition that occurs when an animal generates more heat than it can effectively release via natural cooling methods, such as panting and sweating (Armstrong & Janni, 2020; West, 2003). This increases their body temperature and respiration rate and causes a cascading variety of physical symptoms. For cows, this means that the body temperature rises above the norm of 101.5-102.5°F. Like people, cows are capable of sweating, but this cooling mechanism is impaired when humidity is elevated. This is also one reason why different species, such as poultry, swine and cattle, all experience heat stress but are all affected differently (St-Pierre, 2003).

For dairy cows, heat stress begins at 72-74°F on the temperature-humidity index although some sources say the threshold is in the 60s. Clinical symptoms increase dramatically when the THI is above 80. In extreme conditions, it is possible for heat stress to be fatal. Symptoms are worst when high temperatures persist for multiple days, especially when warm nighttime temperatures do not allow for sufficient recovery (West, 2003).

Heat stress produces a variety of short- and long-term effects. In the short-term, heat stress affects the animal's metabolism, decreasing milk output and dry-matter intake (DMI). One reason for this is that heat stress increases peripheral circulation and directs blood flow away from the udders (West, 2003).

Heat stress produces both qualitative and quantitative changes in milk output. Researchers have identified over 50 metabolites that are affected by heat stress, including some that can be used to track animal health and assess the progression of heat stress symptoms (Tian et al., 2016). Apart from reducing milk output and affecting weekly balance sheets, heat stress has long-ranging consequences due to lower fertility and conception rates during extreme heat (St-Pierre et al., 2003). Calves born to heat-stressed mothers have impaired immune function compared to other groups (Marrero et al., 2021). And they have lower output during their first milking cycles, so it is clear that heat stress can impact multiple generations, not just the current herd.

Milk Production and Climate Change

Key et al. (2014) have estimated the potential economic impact of heat stress using several climate models. This issue is particularly relevant to farmers in the Southeastern United States because high humidity levels reduce the potential for natural evaporative cooling (West, 2003). Consequently, farmers in the Southeast are expected to experience losses over 2% (Key et al., 2014). The effects of heat stress are significant, but how does this critical issue affect farmers?

Heat stress causes $2.4 billion in domestic losses every year. However, no sector experiences larger losses than the dairy industry. Dairy farmers experience an estimated $897 million in annual losses due to heat stress (St-Pierre, 2003). The USDA Economic Research Service (Key et al., 2014) estimates that heat stress costs the U.S. dairy industry $1.2 billion per year or $39,000 per farm. Depending on the climatic model used, the ERS predicts another 0.60–1.35% decline in production from 2010–2030 related to rising temperatures. The annual loss attributable to heat stress in the United States could more than triple to over $2 billion by the end of the 21st century (Mauger et al., 2015).

Due to climate change, experts expect this problem to worsen in coming decades (Ogundeji, 2021). It is also possible that heat stress symptoms will worsen due to genetic improvements related to breeding. High-output cows, such as Holsteins, generate more heat due to metabolism than lower-yielding breeds (Beede & Collier, 1986). As other researchers have concluded, this means that there is less incentive to develop heat-tolerant breeds and hybrid-crosses.

Fortunately, farmers can take steps to reduce heat stress symptoms, such as providing shade and mechanical ventilation in holding areas leading to the milking parlor and providing clean muzzle-deep water after milking (Armstrong & Janni, 2020). Supplements, such as chromium (Kemin, n.d) may also be useful for increasing the animal's adaptability. While some of these solutions are low-cost, misting systems may require significant capital investment as well as wastewater treatment equipment. (St-Pierre, 2023; West, 2003.)

To determine if mechanical cooling, misting and other heat remediation systems are cost-effective, we must first assess the economic impact of heat stress to see how much this issue is costing local farmers and how much they could save by implementing the right technology. That is the purpose of this study.

II. LITERATURE REVIEW

This literature review provides a general overview of previous research on heat stress in dairy cattle and livestock. These studies cover a variety of topics, such as environmental variables, the heat stress threshold, physiological effects and ways to measure heat stress. Several studies use climatic modeling to predict how milk output will change due to rising global temperatures or in response to heat-mitigation technologies. The goal in reviewing these studies is to determine how heat stress affects producers economically while identifying possible ways to analyze this multifaceted problem.

Economic Effects of Heat Stress

With more than 1,900 citations, "Economic Losses From Heat Stress by U.S. Livestock Industries" (St-Pierre et al., 2003) is one of the most-cited studies on the economic losses associated with heat stress. It is notable because it assesses the entire U.S. livestock industry, not just one sector like beef or dairy. Animals surveyed include beef and dairy cows and heifers, finishing cattle, sows and hogs and several types of poultry.

The study examines what happens when animals are raised in conditions outside their thermal comfort zone. It uses USDA and industry data to analyze monthly inventories, plus data from 257 weather stations. Averages were determined based on anywhere from 68 to 129 years of climate data. Animal responses were modeled using climate data, daily heat load indices and the daily duration of heat stress. Monte Carlo techniques extrapolated data 1,000 times for each location. The study analyzed three types of losses: decreased performance, such as growth, milk or egg output and feed intake; increased mortality, and decreased reproduction since conception rates are lower in extreme heat.

Without heat abatement, the study puts total losses across all livestock classes at $2.4 billion annually. According to this study, the dairy industry experiences the largest losses for a single sector. However, optimal heat abatement can bring dairy losses down from $1.5 billion to $897 million per year.

Compared to other studies, St-Pierre et al. (2003) predict smaller losses of 1.5% of the gross income of each animal or about $6 per cow per year, even in the hard-hit states like Texas where intensive heat abatement is recommended. With heat abatement, the authors expect the dairy industry to lose a minimum of $897 million annually. Beef sustained the second-largest losses at $369 million annually. Poultry had the smallest losses at $128 million. With optimal heat abatement, the authors claim that livestock producers can reduce annual heat-related losses to $1.7 billion.

Researchers at the USDA's Economic Research Service (Key et al., 2014) have used a stochastic production function model to see how the THI load, as measured in annual degree hours, affects production efficiency. The researchers used four general circulation climate models to predict possible outcomes. According to this report, the dairy industry bears half the total burden of heat stress for all livestock operations. Based on 2010 prices, heat stress costs the dairy industry $1.2 billion per year, with an average of $39,000 per farm. The study calculates average annual THI loads based on minimum and maximum daily temperatures. Heat stress is expected to decrease dairy production by 0.6-1.35% depending on the climate model. This has a negative impact on both social and producer welfare according to the authors.

Heat Stress in Tennessee

Heat stress conditions vary significantly across different climates. According to St-Pierre et al. (2003), in Florida, cows are exposed to heat stress conditions about 50% of the time. However, nationally, heat stress exposure occurs just 14% of the time. The authors also note that conditions can vary across large states like Texas and California.

St-Pierre et al. (2003) estimate that producers in Tennessee lose 1,678 pounds of milk per cow per year due to heat stress even with minimal heat abatement. For dairy heifers, animals in Tennessee are exposed to 800 hours of heat stress conditions annually. They also estimate that heat stress causes 5.6 deaths per 1,000 cows.

These calculations are based on a minimum temperature humidity index of 65.4 and a maximum temperature humidity index of 82, a very narrow window. Key et al. (2014) predict losses generated by climatic models to be above 2% for Tennessee and other states in the Southeast, including Florida, Georgia and Kentucky. Climate data for Athens, Georgia, (Bohmanova et al., 2007) may be helpful for considering conditions in Tennessee and other parts of the Southeast.

Athens has a warm, humid climate with an average temperature of 17°C (62.6°F) and RH of 72%. Monthly mean temperatures are lowest in January (6°C ≈ 42.8°F) and peak in July and August (26°C ≈ 78.8°F). Relative humidity stays >70% for 67% of all days of the year. Summer months (June, July, August, September) are characterized by hot weather with high humidity of 75%. ... Wet-bulb depression, the difference between the dry bulb and wet bulb temperature, is very low (around 3°C ≈ 37.4°F) in these months. Because of the high humidity, evaporative cooling does not provide any significant relief to the heat stressed cows, and consequently a decline in milk production is observed. In general, efficacy of evaporative cooling systems in Georgia is low because of high humidity, which is present the whole year (Bohmanova et al., 2007).

Proper economic planning is critical to ensure the future of Tennessee's dairy industry. In South Africa's Free State region, the number of dairy farmers decreased by 64% from January 2008 to January 2015 (Ogundeji et al., 2021). The dairy industry in other warm regions, such as the Southeast U.S., may be similarly hard-hit as farmers turn to more productive pursuits.

Thermodynamics and Factors That Affect Heat Stress

Heat stress depends on temperature, humidity, air velocity (wind) and solar radiation (St-Pierre et al., 2003). Most studies do not attempt to quantify all of these. Additionally, these factors are not relevant in all situations. For example, in a bedded pack barn, such as the one used at the MTSU Dairy, there is a minimal amount of solar radiation, so this factor is likely to have less of an impact.

According to West (2003), three things cause reduced milk yield and "efficiency of milk yield." They are air temperature, temperature-humidity index and elevated rectal temperature. Possible solutions to the problem include shade barns, fans and misters/sprinklers and tunnel ventilation.

Heat stress is also influenced by on-farm variables, such as management, breed, stage of lactation and the herd's age distribution (West, 2003). The diary industry has a different breeding season than the beef industry, so the effects are more noticeable (St-Pierre, 2003). Conduction, convection and radiation rates are all dependent on the thermal gradient. As the gradient decreases, heat dissipation is less effective. The temperature-humidity index (THI) is a numeric representation of the effects of temperature and humidity although other studies also consider air velocity, i.e. wind speed (West, 2003).

Understanding heat stress requires in-depth knowledge of the relationship between temperature and humidity. Bohmanova et al. (2007) touch on some of the physiological reasons why cattle are more susceptible to heat. “Humans can dissipate about 190% of their metabolic heat production by evaporation, whereas cattle can dissipate only 105%” (Bianca, 1962).” Additionally, “In humans, the effect of T_{wb} (wet-bulb) on comfort is almost six times as large as that of T_{dp} (dewpoint), whereas in cattle it is only about twice as large.” In other words, people are about three times more sensitive to humidity compared to cattle.

As Yousef (1985) notes, “Cattle can tolerate much higher temperatures at lower relative humidity than swine." Cattle are more effective at dissipating excess heat than swine since cattle have sweat glands while swine must simulate evaporative cooling by covering themselves in mud and allowing it to dry. While cattle appear to have a physiological advantage since they can dissipate heat via sweating and panting, these mechanisms are impaired during hot, humid weather. In these conditions, heat stress affects cattle must faster than it affects swine (Yousef, 1985). Essentially, swine are better adapted to high heat, high humidity conditions, while cattle are more adapted to hot, dry climates.

Thresholds for Measuring Heat Stress

Homeotherms are in the optimal thermoneutral comfort zone when no energy is needed for heating or cooling. According to Lee (1965), stress exists when external forces disrupt the body's normal equilibrium. For cows, the optimal temperature is between 31.1–68°F (Johnson, 1987), while Berman et al. (1985) indicated that the upper critical air temperature for dairy cows is 77–78.8°F Bohmanova et al. (2007). Johnson et al. (1963) reported that milk yield and DMI exhibited significant declines when the maximum THI reached 77. Later research determined that the critical values for minimum, mean and maximum THI were 64, 72 and 76, respectively (Igono et al., 1992). The threshold is typically described as shown in Figure 1:

Figure 1: ***Heat Stress Threshold***

Severe heat waves increase the likelihood for mortality of feedlot cattle, and several hours of THI > 84 with little or no nighttime recovery below 74°F can result in the death of vulnerable animals (Hahn & Mader, 1997). Above 77°F, measures must be taken to reduce the animals' body temperature.

At a temperature of 84.2°F and 40% relative humidity, the milk yield of Holstein, Jersey and Brown Swiss cows was 97%, 93%, and 98% of normal, but when relative humidity was increased to 90% yields were 69%, 75%, and 83% of normal (Bianca, 1965). This demonstrates how dairy farmers with Tennessee and the Southeast may be more affected than producers in more arid regions.

Genetics

Heat tolerance varies by breed. Sharma et al. (1983) found that "Jerseys were more resistant to heat stress in terms of milk production than Holsteins." Based on farm data, producers are already adapting by selecting more heat-tolerant breeds for their region. High-performance animals are more susceptible to heat stress. According to (West, 1994), animals with improved genotypes produce more body heat due to their greater metabolic activity. This applies to cattle and poultry. While West (2003) argues that producers can select for heat tolerance, the traditional practice is to select for performance, which is a factor linked to increased heat stress. Ravagnolo & Mistal's landmark study (2000) also confirms that genetics play a decisive role in determining how well animals tolerate heat.

Physiology, Metabolism and Lactation

Heat stress does not just affect the milk output of affected cattle. Numerous studies, including St-Pierre et al. (2003) and West (2003), show that it also affects milk quality by lowering the percentages of solids, lactose, and protein. In "Integrated Metabolomics Study of the Milk of Heat-stressed Lactating Dairy Cows" (Tian et al., 2016), Chinese researchers studied 53 metabolites that are significantly up- or down-regulated by heat stress due to changes in metabolic pathways. This occurs in part because affected cows significantly reduce their feed intake.

Researchers studied 44 Holstein cows all in second parity and mid-lactation stage. The cows received the same diet. However, one group of 22 cows was subjected to cool conditions (THI 50-55). The other group was exposed to worsening heat conditions ranging from 68 to 80.

The team used the NRC's heat index calculation: $THI = (1.8 \times T_{db} + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T_{db} - 26.8)$. They used spectrometers and other advanced diagnosed equipment to isolate metabolites in the stored samples. Data was then normalized using multivariate analysis, such as Pareto and center scaling, to reduce artifacts and noise.

Of the 50+ plasma-derived biomarkers, researchers found 10 of key significance: lactate, pyruvate, creatine, acetone, β-hydroxybutyrate, trimethylamine, oleic acid, linoleic acid, lysophosphatidylcholine 16:0, and phosphatidylcholine 42:2. Changes in metabolomic processes show that heat stress causes leaks in the blood-milk barrier. They can also be used as a way to track the severity of heat stress symptoms within the herd.

Another issue is that lactating cows produce significantly more heat. Low- and high-yielding cows generated 27-48% more heat than nonlactating cows despite having lower birth weight (Purwanto et al., 1990). Some studies also report that cows treated with the milk-stimulating hormone bST experienced higher rates of heat stress due to increased milk production and other metabolic factors that are not fully understood (West, 2003).

Heat stress produces numerous metabolic effects. It affects the "digestive system, acid-base chemistry, and blood hormones during hot weather; some in response to reduced nutrient intake" (West, 2003). It also affects the cows' nervous system and hypothalamus. Heat stress may reduce mammary circulation as more blood is directed to peripheral areas to increase cooling. Fetus weights for cows that were heat-stressed between day 100 and day 174 of pregnancy were reduced by 22%. Uterine and umbilical blood flows were reduced by 51 and 30% (Reynolds et al., 1985).

Blood becomes more alkaline as C02 concentrations decrease due to panting, which prevents the formation of carbonic acid (West, 2003). Other sources (Cartwright et al., 2023) say that heat stress can lead to acidosis in the rumen due to decreased dry-matter intake and microbial changes.

Heat Mitigation

Strong economic analyses are needed to determine which mitigation strategies are cost-effective for producers in a given area. Key et al. (2014) predict that annual temperatures will increase by 1.45–2.37°F by 2030. If producers take no action to mitigate the effects of heat stress, milk output will decrease by 0.6–1.35%, with larger losses up to 4.4% in certain areas, such as the South. Currently, losses are expected to be moderate with more significant changes expected over time.

Beede & Collier (1986) identified three management strategies to minimize the effects of heat stress: environmental modifications, such as shading, and cooling, selective breeding for heat-tolerance, and improved nutritional management. According to West (2003), a combination of these strategies is needed to achieve desired results and cope with "unknowns associated with global warming."

Shade is the first option. It is estimated that total heat load can be reduced from 30 to 50% with a well-designed shade system (Bond & Kelly, 1955). However, metal structures are criticized for their heat gains, and evaporative cooling systems generate considerable wastewater (West, 2003). Investing in durable cooling equipment also means that farmers must increase their energy use. Data from the 2010 Agricultural Resource Management Survey shows that small dairies spend significantly more on energy than larger farms based on costs per hundredweight (Key et al., 2014). However, evaporative cooling was predicted to improve milk yield for cows yielding 99 pounds per day by 308 pounds in the Missouri to Tennessee area, 507 pounds in southern Georgia, and 705 pounds in Louisiana and Texas during a 122-day summer season (Hahn & Osburn, 1970).

Per St-Pierre et al. (2003), water use and power consumption are important considerations when measuring the cost and benefits of heat abatement technology. Older studies show that air conditioning is not economical or significantly more effective than zoned cooling or shade alone (Hahn et al., 1969). This may or may not be true today due to technological breakthroughs and increases in mechanical efficiency, such as variable-speed technology.

According to Key et al. (2014), climate affects technical efficiency by providing an incentive for producers to invest in mechanical cooling equipment to stay within the thermoneutral zone. Producers in areas that are not as hard hit will be operating below the production frontier by failing to invest in this technology even though they are less affected.

As mentioned earlier, today's dairy industry favors intensive, high-production operations, so there is little incentive to invest in heat tolerant breeds. This leaves nutrition and supplementation as the remaining solutions.

Supplements

Supplements, in addition to adequate nutrition, may also be a way to improve heat tolerance. Apart from providing provisions for physical or mechanical cooling, West (2003) notes that producers must alter their feed rations to provide adequate nutrients and stabilize conditions in the rumen when animals reduce their DMI in response to heat stress. Research also suggests that heat stress conditions can affect the activity of microbes within the digestive system, supporting lactic acid production and potentially leading to acidosis (Cartwright, 2023).

Supplementing with potassium may be helpful since this is the primary cation found in bovine sweat. Lactating cows subjected to hot climatic conditions and supplemented with K well above minimum NRC recommendations (NRC, 2001) responded with greater milk yield (Mallonee et al., 1985; Schneider et al., 1984; West et al., 1987). Australian researchers (Lewis et al., 2021) report that supplementing with betaine and fats increased milk yields by up to 11%. Betaine is a naturally occurring cationic compound from the liver that helps to reduce homocysteine levels and improve nutrient absorption. Commercially available formulas, such as KemTRACE® Chromium by Kemin use chromium, which improves dry-matter intake and insulin sensitivity during periods of heat stress according to 19-peer reviewed studies (Kemin, n.d.).

Ways to Analyze Heat Stress

Economists have used several methods to measure the impact of heart stress on dairy production. The most common method is to compare test day milk yield data to climate records from local weather stations. Bohmanova et al. (2007) focus on comparing high- and low-humidity locations to determine which temperature-humidity index calculations work best based on climatic conditions. They accomplish this by comparing milk production data in Georgia and Arizona to determine which model is most accurate. According to the authors, heat stress thresholds vary by climate. In general, indices that place a higher weight on humidity are more appropriate for humid climates. Researchers used two models to compare the results of the different indices, including a linear regression model based on the degrees of heat stress above the threshold. Estimates compare the sum of yearly milk yield losses with the goal of selecting the index that predicted the largest milk losses.

In St-Pierre et al. (2003), the authors calculate THI min and max. Min is the minimum temperature and maximum humidity, and max is the maximum temperature and minimum humidity. For more information about this THI formula, see Ravagnolo & Mistal (2000).

Ogundeji et al. (2021) use the same approach as St-Pierre et al. (2003) to estimate the impact of climate change on South African dairy farms. However, this study uses a different THI mentioned by Du Preez (2000). They used a THI threshold of 70 followed by a threshold of 65 for comparison reasons and sensitivity testing. This model considers daily maximum (THI max), the fraction of the day that THI is above the threshold (D), and THI threshold. The formula for milk loss (L/cow/day) due to heat stress is given as: Loss= α (THI_{max}−$THI_{threshold}$)2×D where $\alpha = 0.065$.

The goal was to compare baseline losses from 1950-1999 to future losses from 2040 through 2070. The study also calculates a coefficient of variation for each of the three geographic areas surveyed. The highest losses were recorded during the late summer for each region. They concluded that seasonal cycles in production loss exist due to the nonlinear dependence of the milk-production loss model on daily temperature and humidity. Next, the researchers projected losses with abatement strategies in place. The results show that a moderate abasement model with sprinklers and ventilation can reduce losses by more than 50% in all scenarios.

While most early studies look at same day conditions, others have found that the total number of heat stress hours in the preceding four days have the greatest impact. When the THI is around 80, the effects are noticeable in as little as one day. West et al. (2003) report that environmental conditions in the preceding two days had the greatest effect on milk yield during hot weather. This suggests that cows can handle short periods of high heat, but productivity declines the longer the stress persists. According to Igono et al.

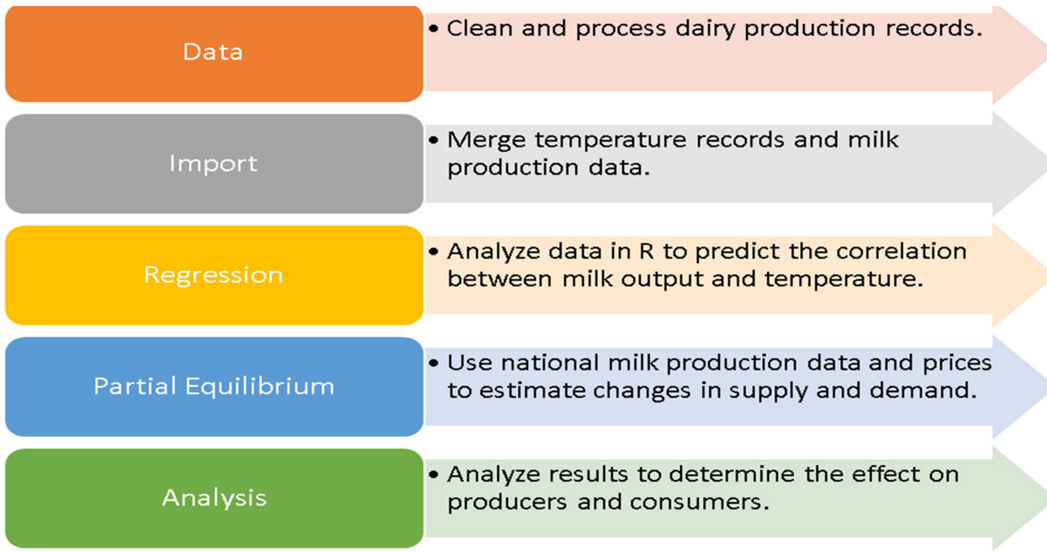
(1992), just three to six hours of cooler temperatures around 69.8°F can reduce production losses.

Analyzing the effects of heat stress is a complex problem. As Ogundeji et al. (2021) note, “there is limited literature on the economic impact of heat stress on milk production.” Additionally, studies fail to address “farmers perception and adaptation strategies.” When assessing heat mitigation technologies, such as mechanical ventilation and misting, it is important to consider whether farmers will be willing to adopt these strategies in addition to determining whether they are economically feasible.

III. METHODS

This two-part study uses statistical methods and applied economics to determine how dairy farmers and consumers are affected by heat stress. First, we conduct a linear regression analysis to determine the correlation between temperature (independent variable) and milk output (dependent variable). By identifying the slope of this line, we can create a function showing milk output as a product of temperature. Next, we use published information on the elasticity of demand for the dairy industry to estimate the change in consumer and producer surplus due to heat stress. This multistep process shown in Figure 2 allows us to estimate the financial impact of heat stress on the economy.

Figure 2: ***Methodology Flowchart***



To determine the relationship between heat stress and milk production, records on historic production were obtained from the MTSU dairy located on Guy James Road in Murfreesboro, Tennessee. Data were collected during the normal course of business and were not prepared for research purposes. Based on the availability of consistent records, we identified a sample period spanning over seven years from September 9, 2014, through March 30, 2022. The dataset includes over 2,600 entries that were examined for validity. Outliers representing partial daily values (one milking per day) were excluded from the dataset. Other problematic values, such as duplicates and delayed reports occurring on holidays, were assessed manually.

Daily milking reports were provided in binary code using the Data Interchange Format (.dif). For ease of use, files were renamed using a bulk utility tool, and additional header rows were removed as part of data cleaning. The next step was to average the daily milk output values to determine mean production per day, per head for the herd. The value for each day was then exported to Microsoft Excel and paired with the recorded daily high temperature for that date. Calculations and data exporting were automated using Visual Basic for Applications, which has the ability to work with both binary files and Excel spreadsheets.

Temperature data was secured from the Southern Regional Climate Center (SRCC, 2023). In this case, data was secured from the nearest major weather station, which is located at the Nashville International Airport. A national median temperature of 52.7°F (Current Results, 2023) was used was used as a baseline for the model with a 2.7°F temperature increase expected due to global warming (IPCC, 2013). For comparison purposes, a higher base temperature of approximately 72°F was used to represent conditions in a warm area, such as Florida (Osborn, 2023).

Data Analysis: Regression

To assess the relationship between temperature and milk output, we used an ordinary least squares regression to find the path of best fit. The resulting equation can be used to estimate milk output at any given temperature, and it allows us to see when production is optimized and when heat stress begins. In this case, the regression analysis was completed using the statistical software R.

The regression formula also includes a quadratic term to test for the possibility of a quadratic functional form (i.e. Extreme heat and cold may both impact average daily production). This method allows us to determine heat stress as a function of temperature, so we can estimate milk output in a variety of conditions.

Data Analysis: Elasticity of Demand and Consumer and Producer Surplus

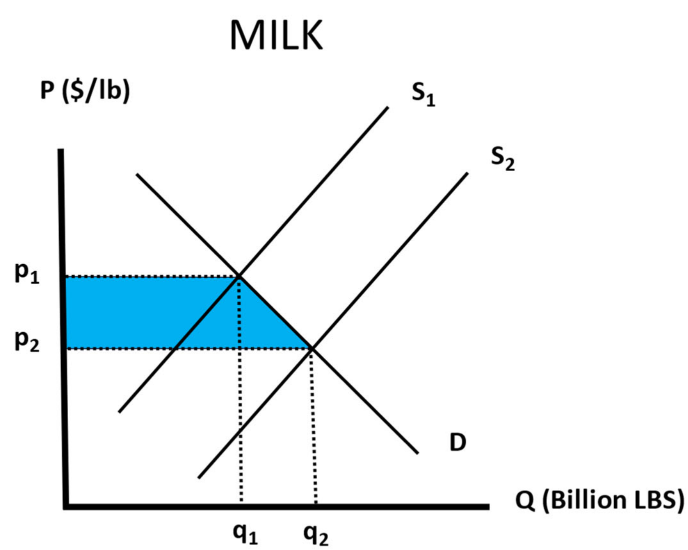
Merely comparing temperature and milk output does not show how the producer or consumer is affected, so it is necessary to place dollar values on these figures, which is accomplished using a partial equilibrium model to conduct welfare analysis.

To calibrate the general equilibrium model, we used data from the USDAs National Agricultural Statistics Service. This agency provides annual data on total milk output as well as daily and annual production per head. It also tracks average milk prices and total revenue, among other data points.

To complete a partial equilibrium analysis measuring producer welfare as described by Just et al. (2004), we also need an own-price elasticity of demand. The elasticity of demand is determined by dividing the percentage change in quantity by the percentage change in price. Since dairy is part of a complex multiproduct market, data is often disaggregated by end use. Additionally, studies on elasticity of demand tend to focus on consumers' buying habits. However, we were able to find a suitable estimate. Zhang & Alston (2018) report a Marshallian own-price elasticity of demand for farm milk between -0.43 and -1.20 with a best estimate of -0.8 based on preferred parameters and data censoring. This study looks at dairy as a production input for the manufacturing industry. Price changes derived from the partial equilibrium model are based on an elasticity of demand of –0.8 as reported by Zhang & Alston (2018).

The elasticity of demand allows us to see how milk consumption responds to changes in the milk supply. As milk output decreases, we expect the supply curve to shift to the left, which would result in a higher equilibrium price and smaller equilibrium quantity. This also means that the total consumer surplus and producer surplus would shrink.

Figure 3: ***Supply, Demand and Producer Surplus***



By determining the change in consumer and producer surplus, we can determine total economic losses to society. This is accomplished by measuring the area between P1 and P1 and equilibrium point E1 and E2 (Figure 3). This information can then be used to help dairy farmers determine when mechanical heat remediation is a financially viable solution.

IV. RESULTS

The goal of the regression analysis is to determine the relationship between temperature and milk production as a proxy for animal welfare, which in turn can be used to determine the impact of increased temperatures on both producer and consumer surplus. Results can be seen in

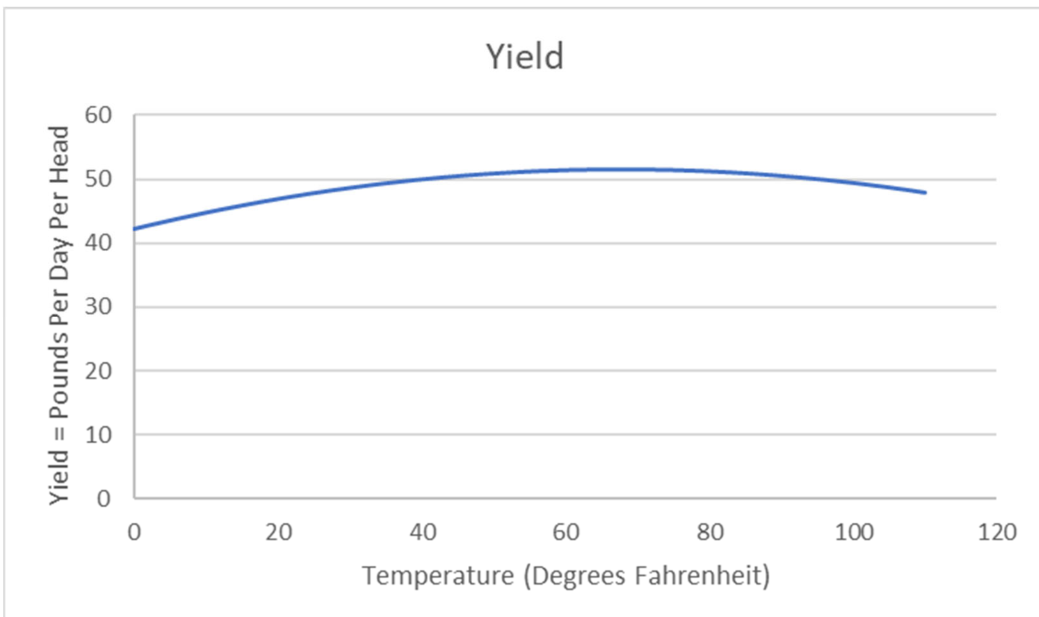
Table 1. Based on the overall *F*-statistic, the model is statistically significant (alpha = 0.001). The estimated coefficients are also statistically significant (alpha =0.001). In spite of this high degree of statistical significance, the model lacks explanatory power with an R^2 of 0.01.

Table 1: ***Regression Results***

Variable	Estimated Coefficients	Standard Error	T-Statistic	P-Value	
Intercept	42.2570482	1.7411713	24.269	< 2e-16	***
Temperature	0.2713517	0.0532066	5.1	3.63E-07	***
Temperature^2	-0.0020344	0.0003898	-5.218	1.94E-07	***
F-statistic: 13.77 on 2 and 2686 DF, p-value: 1.127e-06***					
***Statistically significant alpha = .001					

Typically, regression coefficients are best interpreted as slopes, however the estimated model is nonlinear as it includes the quadratic term Temperature^2. The temperature coefficient implies that for every one degree increase in temperature milk output will increase by 0.27 lbs. This result seems counterintuitive since heat stress is typically shown to reduce milk output. However, as discussed previously, both heat and cold stress reduce milk production. Hence the quadratic term allows us to fit a concave to curve to the data in order to account for this, as can be seen in Figure 4, which shows the predicted daily output per head as a function of temperature.

Figure 4: ***Expected Milk Production***



This model predicts that production will peak at 68°F, thus showing that there is an optimal cow comfort zone that maximizes production (Figure 4). It is important to note that the further the temperature deviates from the comfort zone the larger the drop in production. A temperature increases from 70 to 80°F, for example, results in a 0.29 lbs per day decrease. However, an increase from 90 to 100°F will decrease production by

1.09 lbs per day. Likewise dropping from 70 to 60°F decreases output by a negligible 0.11 pounds per day while dropping from 50 to 40°F causes a 0.91 pound decrease.

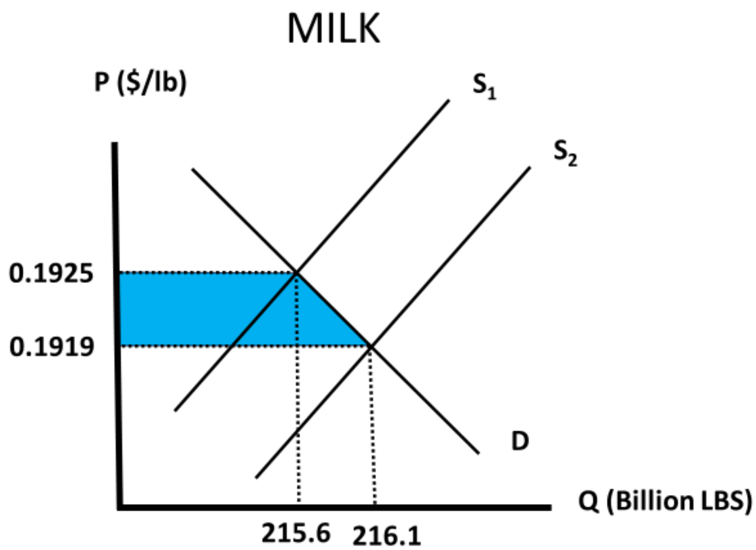
Table 2: ***Change in Milk Production by Temperature***

Temperature °F	Yield in Lbs	Δ Production	
		Rising Temp	Falling Temp
0	42.25		-2.51
10	44.76	2.51	-2.11
20	46.87	2.11	-1.71
30	48.58	1.71	-1.31
40	49.89	1.31	-0.91
50	50.8	0.91	-0.51
60	51.31	0.51	-0.11
70	**51.42**	**0.11**	**-0.29**
80	51.13	-0.29	-0.69
90	50.44	-0.69	-1.09
100	49.35	-1.09	-1.49
110	47.86	-1.49	

According to the USDA's National Agricultural Statistics Service (NASS, 2023), the U.S. dairy herd averaged 9.3 million head per year between 2013 and 2022 as shown in Table 3. Over the past 10 years, these cows have generated between 59.80-66.17 pounds of milk per day with a mean of 63 pounds per day. This results in an average annual yield of 23,085 pounds per head. The nation's dairy herds produce over 215.5 billion pounds of milk annually. If production were to increase by 0.24%, as the model predicts, total milk output would rise by another 500 million pounds to just over 216 billion pounds.

Even though 500 million pounds seems to be a very large number, it is relatively small considering the scale of dairy output in the U.S. Nonetheless, any such change in production would cause the supply curve to shift outward as shown in Figure 5.

Figure 5: ***Elasticity of Demand, Milk Supply and Farmgate Prices***



If the elasticity of demand for industrial milk is -0.8% as estimated by Zhang, & Alston (2018), we predict that farmgate milk prices would drop from 19.25 cents to 19.19 cents per pound. Although milk output increases, which should be good for the producer, profit actually decreases due to lower prices. Assuming that the increase in temperature imposes no additional cost on the farmer, then any change in revenue translates directly into a change in profit, it has also been shown that a change in producer profit is exactly equal to a change on producer surplus, which is the standard tool economists use to represent producer welfare (Just et al., 2004). This model predicts that, nationwide, farmers will lose just under $38 million, or approximately $4.05 per head. Thus, one may conclude that increasing temperatures may be good for cows, but bad for dairy farmers.

Consumers, on the other hand, will benefit from the increased production and lower prices (Just et al., 2004). The blue area shown in Figure 5 represents the change in consumer surplus of $123.1 million.

When looking at a higher base temperature, the inverse is true. At a higher starting temperature that's above the optimal zone, further increases in temperature cause a decrease in production. Increasing from 72°F to 74.7°F would cause a 0.06 pound drop in daily production, or 21.9 lbs per year per head. Due to a decrease in the supply, the price would then increase to 19.273 cents per pound. In spite of the small price increase, revenue would still drop by just over $3 million nationwide due to the decrease in production. The higher price also results in a $50 million drop in consumer surplus nationwide. This illustrates the harm caused by extreme temperatures.

V. DISCUSSION

This study yielded four unexpected findings. First, as evidenced by the statistically significant quadratic term in the regression model, dairy cattle are subject to both heat and cold stress. Second, total milk production could potentially rise as global temperatures rise. Third, increased production is potentially harmful to dairy farmers due to an inelastic demand for fluid milk. Finally, consumers may benefit due to the lower price of milk. These results rely on the fact that the average annual temperature in the U.S. is lower than the optimal thermal zone for milk production.

The primary challenge when analyzing heat stress is the data. While this study included over 2,600 daily records, the herd size is limited to approximately 50 head. Other major studies (St-Pierre, 2003; Ravagnolo, 2000) have looked at 12,500 to 15,000 animals over long periods of time. The available data lacked several important variables such as animal health, genotype and lactation stage. Health is likely a deciding factor in the animal's overall production, and it is likely correlated with other measurable production data, such as dry-matter intake and movement. However, these factors were not analyzed.

Although not an issue for this study since we are only looked at one independent and dependent variable, milk production is fraught with multicollinarity and confounding factors. As Pourhoseingholi et al. (2012) note, "A confounder is an extraneous variable whose presence affects the variables being studied so that the results do not reflect the actual relationship between the variables under study."

Multicollinearity describes a close relationship between two or more independent variables and the output variable. When multiple predictor variables are correlated, neither can independently determine the outcome (Studenmund, 2001). In this case, we know that both temperature and dry-matter intake are closely related, therefore neither can accurately predict milk output since both factors have an influence. This limits potential ways to refine the fit of the regression.

Due to these limitations, our model does not assess the relationship between milk output, temperature and underlying factors. This is one possible reason for the low R^2

value. The fit of the model may also be affected by random variability in milk production that causes excess noise in the data. It is also possible that although diary output and temperature have a nonlinear relationship (Ogundeji, 2021), the quadratic term may not adequately explain production trends, particularly at extremely high and low temperatures.

While we attempted to improve the fit of the model by adding a time lag and using natural logarithms, this did not improve the results. Multivariate analysis could be one solution for taking a closer look at the relationship between individual factors that affect milk production (Pourhoseingholi et al., 2012).

Climatic assumptions also affect the results. Our model used an expected temperature increase of 2.7°F (IPCC, 2013) compared to 1.45-2.37°F used by Key et al. (2014). The average starting temperature of 52.7°F (Current Results, 2023) was likely a deciding factor behind these results. While this number reflects the national average, it may not accurately reflect conditions in a given geographic area, such as Tennessee, which is why we opted to include a higher base temperature as well.

To determine if these findings are reliable, it is important to analyze data from a variety of farms and geographic locations, not just one dairy in a relatively mild climate. It is likely that climate change will decrease production in hot areas, such as Arizona and Georgia, while increasing production in cooler areas, such as Wisconsin. Additionally, the effects of temperature may also be more significant on high-yielding animals producing more than 60 pounds of milk per day.

Our data considers the actual (dry-bulb) temperature rather than the adjusted wet-bulb temperature, which accounts for the evaporation rate. Since we are only looking at temperature, we do not consider the relationships between temperature and humidity like the temperature-humidity index does. In this case, providing a daily measure for constantly changing humidity values proved too complex for this project. Temperature-only results can be viewed as a starting point since it is likely that excessive humidity will increase the impact of heat stress at any given temperature.

One issue with many previous studies is that they focus solely on conditions that contribute to heat stress. Looking at an isolated scenario, such as a heat wave, is an easy way to prove that heat stress decreases milk production, but it does not give a true measure of how these variables relate in all situations. Key et al. (2014) focus on assessing the total heat load, which is defined as the total "amount of humidity-adjusted heat that animals are exposed to" annually. Then, they use an econometric production model to predict how dairy productivity will respond to an increase in the heat load. \

If we were only looking at heat load and milk production as other studies have (St-Pierre et al, 2003; Ravagnolo, 2000; Key et al. 2014), we would also have projected a decrease in production. However, we used a quadratic term to account for both heat and cold stress. This model shows that heat stress begins at temperatures above 68°F, which is similar to the findings reported by previous research (Bohmanova et al., 2007).

The most surprising result is that rising global temperatures mean that livestock in some areas will experience less cold stress and spend more time in the thermoneutral zone. This is contrary to prevailing views that climate change always results in negative consequences. In reality, negative situations can have positive outcomes either directly or indirectly. It is possible that some people will be better off due to global warming even if the majority are worse off.

Although our model predicts annual milk production to increase slightly by 0.24%, or about 500 million pounds, producers are actually worse off because an increase in production pushes the supply curve outward and drives the market price down. This is not entirely surprising since factors that increase production, including technological change, are shown to reduce on-farm profits according to previous research (Alston & Martin, 1995).

There is also a need for additional research into the effects of cold stress. This is something that has been virtually ignored in previous studies on heat. By looking at just a portion of the data, researchers may be overlooking important seasonal trends. A preliminary search of the James E. Walker Library database at MTSU yielded over 4,500 results for the search terms “heat stress” and “dairy cattle.” The terms “cold stress” and “dairy cattle” yielded just 95 results. Experts like Smith & Harner (2012) who discuss cold stress in the textbook “Environmental Physiology of Livestock” tend to focus on the physiological effects of cold conditions, particularly on the youngest members of the herd. Current science also suggests that temperature is important for up- and down-regulating certain immune functions (Lacetera, 2012). Therefore, spending some time outside of the thermoneutral comfort zone may actually be beneficial for the animal’s health.

One of the only studies that assesses cold stress and dairy (Angrecka & Herbut, 2015) found that wind chill temperatures of 12°F reduced milk output by 4.4 pounds with a strong correlation of r = 0.72-0.89.

It is important to note that when researchers like Mauger et al. (2015) estimate that the loss attributable to heat stress in the United States of America could more than triple to over $2 billion by the end of the 21st century, a small fraction of total revenue, they are only looking at how dairy production changes over time. Since heat stress and other environmental stressors are already occurring, we have no baseline to which we may compare. There is no such thing as a perfect climate, so the best we can do is estimate the changing impact of environmental factors over time.

Table 3: ***U.S. Milk Production 2013-2022***

Year	Pounds	Revenue	Head	Daily Production
2022	226,462,000,000	$57,974,272,000	9,377,000	66.17
2021	226,293,000,000	$42,090,498,000	9,442,400	65.66
2020	223,309,000,000	$40,418,929,000	9,342,600	65.49
2019	218,441,000,000	$40,848,467,000	9,353,400	63.98
2018	217,568,000,000	$35,463,584,000	9,432,100	63.20
2017	215,527,000,000	$38,148,279,000	9,368,500	63.03
2016	212,451,000,000	$34,629,513,000	9,312,400	62.50
2015	208,508,000,000	$35,654,868,000	9,311,900	61.35
2014	206,048,000,000	$49,451,520,000	9,208,600	61.30
2013	201,260,000,000	$40,453,260,000	9,221,200	59.80
Mean	215,586,700,000	41,513,319,000	9,337,010	63
Min	201,260,000,000	34,629,513,000	9,208,600	60
Max	226,462,000,000	57,974,272,000	9,442,400	66

Source: USDA NASS QuickStats

Despite challenging conditions, including environmental factors, milk production has increased year-over-year across the past decade as shown in Table 3 (NASS, 2023.), so it is unlikely that the entire dairy industry is at risk. Technical and genetic improvements may already be helping dairy farmers weather adverse conditions, and producers must continue to adapt to changing circumstances to remain profitable.

VI. CONCLUSION

Temperature is a complex, ever-changing variable that is closely tied to other environmental conditions, such as humidity, wind speed and sun exposure. Cows and all animals are sensitive to extreme heat and extreme cold. As living beings, we all like to be comfortable, and as economists, perhaps we can put a price on what that comfort is worth.

Quantifying the actual or expected loss allows business owners and farm operators to conduct a cost-benefit analysis to see which mitigation measures are most cost-effective. In the absence of such an analysis, the most practical recommendation is for major dairy producers to invest in low-cost measures, such as shade, milking parlor ventilation and watering stations. It may also be more profitable for producers to operate in areas with moderate to cool climates, such as California and Wisconsin, as they do currently, while avoiding high-heat locations, such as Florida and Arizona.

Dairies that operate in subtropical and tropical areas, including the Southeast, can use climatic data to estimate potential costs and possible gains of investing in heat-mitigating technology—like air conditioning. It is also possible that dairy products may command higher prices in these areas due to local supply and demand trends. This creates more incentives for producers to invest in production-enhancing technologies. Although, ultimately, increasing production only increases the supply, pushing the equilibrium quantity up and the equilibrium price down.

This research underscores the need for more comprehensive climatic studies on heat stress and cold stress. If we are not looking at data from a variety of seasons, we are not getting an accurate picture of how climate affects dairy production. We are only confirming what we already know, that heat stress decreases dry matter intake and dairy output.

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