Impacts of Climate Change on Milk Production in the United States

Yoram Bauman[1], Eric P Salathé Jr[2,3] , Guillaume S Mauger[3], and Tamilee D Nennich[4]

** Corresponding author: Yoram Bauman. Phone: 206-351-5719, FAX: 206-616-2465, E-mail: yoram@uw.edu, Address: Box 355679, University of Washington, Seattle WA 98195-2802*

[1]Program on the Environment, University of Washington, Seattle, and Institute of Global Low-Carbon Economy, University of International Business and Economics, Beijing

[2]Science and Technology Division, University of Washington, Bothell

[3]Climate Impacts Group, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle

[4]Department of Animal Sciences, Purdue University

Abstract

Climate change is likely to affect milk production because of the sensitivity of dairy cows to excessive temperature and humidity. We use downscaled climate data and county-level dairy industry data to estimate Holstein milk production losses in the conterminous United States. We find that there is significant geographic variation in production losses and that regions currently experiencing the greatest heat-related impacts are also projected to experience the greatest additional losses with climate change. On a national level, we project that climate impacts could reduce end-of-century milk production per cow by 6.3% relative to baseline production.

Key words: Climate change adaptation, economic impacts, milk production, dairy production, heat stress

Acknowledgements

The authors acknowledge the skilled assistance of Robert Norheim in providing GIS analysis and maps used in this paper and of Hye Jin (Jenny) Chang in gathering dairy industry data. This research was supported in part by the Climate Impacts Group of the Joint Institute for the Study of the Atmosphere and Ocean under NOAA Cooperative Agreement No. NA17RJ1232.

Introduction

Excessive heat and humidity causes heat stress in dairy cows, which results in reduced milk production. Because the United States contains significant variability in climatological relative humidity and diurnal temperature range, the sensitivity of milk loss to warming is likely to vary geographically. This is especially important given that milk production is highly concentrated in a relatively small number of counties across the U.S. (Figure 1 shows the distribution of dairy production by county, based on USDA 2011b).

The purpose of this paper is to combine current climate projections for the conterminous United States with current data on dairy production in order to estimate the potential impacts of climate change on the dairy industry and the variation of these impacts geographically. These county-level estimates are an improvement over previous research—e.g., Hahn (1999), West (2003), Hatfield et al. (2008), and Mader et al. (2009)—which has tended to use broad geographical regions or case-study-type approaches. One exception is Hayhoe et al. (2004), which estimated end-of-century losses in California's main dairy-producing counties to be as much as 22% under a high emissions scenario. However, that study used data from Sudan (Ahmed and El Amin, 1997) to estimate production losses. As shown in Figure 2, this approach is a reasonable fit for climates that are very hot and very dry—such as Maricopa, Arizona—but it does not adequately describe the effects of warming in other climates.

For our assessment—as with much of the prior literature—other variables were held constant in order to focus on the effects of climate change. Specifically, the baseline level of milk production per cow is held constant, a significant assumption given that milk production per cow increased 16% between 2001 and 2010 (USDA 2011a) and is projected to almost double between 1985 and 2020 due to selective breeding and improved management practices (USDA 2010, p83). Historically, these increases have sometimes been at odds with improvements in heat tolerance – selection for increased milk production, for instance, has resulted in reduced heat tolerance in diary cows (Ravagnolo and Misztal, 2000). Our intent in this paper is to indicate the cost of increased heat stress in the absence of such changes, against which the costs of adaptation may be balanced.

Methods

This study is based on some assumptions that are common to the dairy industry. The analysis assumes that dairy operations are managed such that cows are calving continually throughout the year, resulting in herd attributes that remain stable regardless of season. Our analysis focuses on the amount of lost milk production, measured in kg/day. However, in a few isolated instances—notably in calculating percentage losses and other economically relevant variables—it is necessary to estimate a baseline level of milk production per cow in the absence of heat stress. For simplicity, we use an estimate of 30 kg/day. This is close to published estimates (USDA, 2012), and moderate changes in this baseline do not affect our conclusions.

In evaluating the effects of climate change, we follow the approach in St-Pierre et al. (2003; hereafter SP2003) because of its tractability and extensive literature review. Based on data reported in the literature, they estimate the physiological effects of heat and humidity on Holstein dairy production by considering diurnal variations in a single parameter, the temperature-humidity index (THI). The THI is calculated from temperature and relative humidity ($0 \leq RH \leq 1$) according to the formula from NOAA (1976):

$$THI = (1.8 \cdot T_{air} + 32) - (0.55 - 0.55 \cdot RH)(1.8 \cdot T_{air} - 26), \qquad (1)$$

where T_{air} is the air temperature in degrees Celsius. (See also West et al., 2003, Ravagnolo and Misztal, 2000, and Ravagnolo et al., 2000). Note that THI increases linearly with air temperature if relative humidity is held constant, and that THI is simply air temperature in Fahrenheit if RH=100%.

The formula for milk loss per day in SP2003 depends on two meteorological parameters related to the diurnal cycle of THI: (i) THI_{max}, which is the daily maximum, and (ii) D, which is the fraction of the day ($0 \leq D \leq 1$) that THI is above a threshold value, $THI_{threshold}$ (see Appendix, SP2003). Using these variables, SP2003 gives the loss of milk production due to heat stress (in kg/day) as

$$\mathrm{LOSS} = \alpha\,(\mathrm{THI}_{\mathrm{max}} - \mathrm{THI}_{\mathrm{threshold}})^2 \times \mathrm{D}. \qquad (2)$$

Equation 2 includes two empirical parameters: $\mathrm{THI}_{\mathrm{threshold}}$, the value above which heat stress affects milk production, and α, a regression coefficient. Following SP2003, we use $\alpha = 0.0695$ and $\mathrm{THI}_{\mathrm{threshold}} = 70$, the latter corresponding to a temperature of 29.3°C (84.7°F) with RH=0%, 23.6°C (74.6°F) with RH=50%, and 21.1°C (70°F) at RH=100%. Also consistent with SP2003, we assume that the diurnal cycle is sinusoidal and that the humidity and temperature cycles are exactly opposite in phase. This allows for a simple analytic expression for D in terms of $\mathrm{THI}_{\mathrm{threshold}}$ and the daily minimum and maximum values of THI.

Holding RH constant, milk loss increases with temperature at a greater than linear rate, due to both the quadratic dependence on $\mathrm{THI}_{\mathrm{max}}$ and the factor D (duration of elevated THI), which increases with temperature. Holding temperature constant, milk loss increases with increasing humidity, in part because of the direct impact of humidity on $\mathrm{THI}_{\mathrm{max}}$, but also because humidity has an effect on the diurnal cycle of temperature. Humid regions exhibit a smaller diurnal temperature range due to reduced radiative cooling at night, so for the same $\mathrm{THI}_{\mathrm{max}}$ at mid-day one would expect D, the duration of elevated THI, to be longer in humid regions. These sensitivities are highlighted in Figure 2, which shows results for a number of prominent milk-producing regions.

Another important aspect of Equation 2 is that LOSS must be computed at the daily time step, using daily maximum temperature, minimum temperature, and humidity rather than long-term averages. Since the LOSS equation is highly non-linear in temperature, the reduced milk production on warm days is not equally compensated by increased production on cool days. As a result, even if the average conditions at a particular location do not suggest much risk from heat stress, a substantial reduction in milk production could result from episodic heat events. It is therefore necessary to use daily temperature data to accurately assess the implications of heat stress for dairy production: monthly (or longer) averages are not sufficient.

We note that our estimates do not account for some of the indirect impacts of heat stress, such as reduced reproductive efficiency or availability of food and water, or for factors unrelated to climate that may influence milk production. In addition, our estimates do not include milk losses from temperatures that are too cold rather than too hot. Although such losses would be reduced in a warming climate, Kadzere et al. (2002, based on Hamada, 1971) estimate that the lower critical temperature for cows producing 30 kg of milk per day is between -37 and -16 degrees C. Cold stress therefore has a relatively small impact on dairy production in the conterminous US.

For the economic analysis, we follow the same methodology as SP2003, updated using livestock data from 2009 and the 2006-2010 market year average milk price of $0.350/kg (USDA 2011b; SP2003 use livestock data from 2000 and a price of $0.287/kg).

Data

Current and future temperature

Daily temperature data for 1950-1999 were obtained from the 1/8° resolution gridded dataset developed by Maurer et al. (2002). The dataset, which includes daily minimum and maximum temperatures, is based on weather observations from the National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer (Co-op) stations. As described by Maurer et al., the data are gridded using the synergraphic mapping system (SYMAP) of Shepard (1984), and adjusted to the mean grid cell elevation using an assumed lapse rate of -6.5 K/km.

Future daily temperatures for the 2050s and 2080s were obtained by adding projected temperature changes to the historic daily data. Monthly-average temperature projections were obtained at 1/8° resolution (Maurer et al., 2007) from the Lawrence Livermore National Laboratory's "Green Data Oasis". The data were derived from the CMIP3 (Coupled Model Intercomparison Project phase 3) archive of global climate model (GCM) output. We used results from the A1B emissions scenario (Nakicenovic et al. 2000), a middle-of-the-road scenario for 21st century greenhouse gas emissions. An ensemble average of all 16 available GCMs was used to project future temperature changes. Specifically, differences were computed for the 30 years surrounding the decades of the 2050s (2040-2069) and the 2080s (2070-2099) relative to the final 50 years of the 20th century (1950-1999). Differences in temperature were computed separately for each calendar month and applied to the daily historical record to obtain an estimate of future climate conditions. The simplicity of this method ensures that the realism of the historical record, in particular the geographic and temporal distribution of heat episodes, is retained. Note that as a consequence, this method implicitly assumes that the probability distribution and sequencing of weather events in the historical record are representative of what will occur in the future. Since it is not clear if GCMs can reliably predict such changes, we take the conservative approach of only considering mean changes in temperature. We also only consider changes in daily average temperature. Under climate change, minimum temperatures are expected to increase more than maximum temperatures. This means that our estimates, which assume an equal amount of warming for both minimum and maximum temperatures, are likely to underestimate the impacts to dairy production, since a relative increase in minimum temperatures would imply a longer duration of afternoon heat stress.

Humidity

Humidity data were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group (http://www.prismclimate.org, creation date 4 Feb 2004, Daly et al., 2002). The dataset consists of monthly mean values of dew-point temperature (see note 1 below), gridded at 1/8° resolution, for 1950-1999. Monthly mean values of dew-point temperature were combined with the daily values of minimum and maximum temperature described above to compute daily-varying morning and afternoon relative humidity (RH_{AM}, RH_{PM}). We assume that the dew point is never greater than the minimum temperature (dew formation is assumed in these cases) but that dew point temperatures, and thus the moisture content of the air, are otherwise constant throughout each month. The assumption excludes some processes that affect daily variations in humidity: processes such as moisture transport in weather events, evaporation, and precipitation can all alter the local moisture content of the air on daily time scales. Despite this limitation, the method does include the dominant geographical variations in humidity and the diurnal cycle that are important in understanding heat stress in dairy cows.

For the future projections, we assume that relative humidity is the same as in the current climate. Climate models are known to have difficulty in accurately simulating humidity, in particular at ground level. The assumption of constant relative humidity thus avoids this source of uncertainty while nonetheless accounting for the increase in water-holding capacity of warmer air. This is consistent with the approach of projecting future temperature changes onto the observed daily time series, since similar weather conditions would suggest little change in relative humidity.

Results

Sensitivity of milk production loss to temperature

The combined effects of diurnal temperature range and humidity, which vary considerably across the U.S., result in significant geographic variations in the sensitivity of milk production to warming. To illustrate this geographic dependence, milk loss was computed from Equation 2 using the observed daily meteorological data for several counties around the U.S. The results for daily milk loss as a function of daily average temperature are shown in Fig 2, using results from a representative sample of U.S. dairy-producing counties. Sensitivity to production losses varies dramatically among the five counties shown. For Okeechobee FL, which is both hot and humid, production losses commence at a lower temperature and increase at a much steeper slope than in the hot but dry county of Maricopa AZ. Lancaster PA and Tulare CA fall midway between these two extremes due to moderate relative humidity. An interesting case is Tillamook OR, which despite being quite cool and seldom experiencing daily mean temperatures over 25°C nevertheless shows production losses beginning at about 15°C, reflecting heat stress resulting from very humid days with warm nights. This strong geographic variability in the heat sensitivity of milk production follows directly from the geographic variability in temperature, diurnal temperature range, and humidity.

Previous approaches that model milk production loss as a simple linear relationship with temperature give the same sensitivity to warming regardless of whether an area is climatologically humid or dry. Figure 2 includes the observed milk production results from

Ahmed and El Amin (1997), which are the basis for the 1.15 kg/°C sensitivity used in Hayhoe et al. (2004) and other studies. Hayhoe et al. used two thresholds for heat stress – 25°C and 32°C – beyond which they modeled milk loss using the linear 1.15 kg/°C sensitivity. These linear relationships are also plotted for comparison. The linear relationship with the 32°C threshold clearly does not match the observations. In fact, 32°C is the coolest weekly average temperature observed by Ahmed and El Amin (1997), so these data cannot be used to infer the production level of unstressed cows without significant extrapolation to lower temperatures. Comparing the loss estimates of the THI method (Equation 2) to those of the linear Ahmed and El Amin (1997) relationship, it is clear that the latter is only consistent with the driest climates of the United States. Indeed, in Sudan the weekly average relative humidity observed by Ahmed and El Amin ranged from 11% to 18%. Since humidity is an important determinant of heat stress and varies significantly across the conterminous U.S., a model based solely on temperature is not sufficient to capture observed variations in U.S. dairy production.

Annual cycle of loss at particular stations

Since Equation 2 is non-linearly dependent on daily temperature and humidity, it follows that there should be a strong seasonal cycle in production loss. Figure 3 shows the mean annual cycle of lost milk production for 10 U.S. counties (listed in Table 1), selected to represent a cross-section of the primary milk-producing regions of the country. For each location, the figure shows the mean daily loss for each day of the year; for clarity, the data were smoothed using a 7-point moving average. Each plot shows the daily milk production loss due to heat stress predicted from Equation 2, for both the historical period and the 2050s. For the historical period only, each plot also includes the linear loss estimates used by Hayhoe et al. (2004; loss of 1.15 kg/°C for 25°C and 32°C thresholds, see Figure 2).

Figure 3 highlights a number of interesting implications regarding climate impacts on milk production. First, there is a striking contrast between production losses in different regions, ranging from Tillamook OR, where losses are negligible, to Maricopa AZ, where the mean daily losses in summer approach 50% of total production for the historical period. Large contrasts are seen across all 10 locations shown, some stemming from fairly small differences in climate.

Second, while production losses under historic conditions are mainly confined to summer, climate change yields losses from spring to autumn in many locations. Third, the difference between loss computed from Equation 2 and the linear temperature relationship from Hayhoe et al. is strongly dependent on the ambient humidity of each location. In the dry climate of Maricopa AZ, for instance, the two are in fairly close agreement. In contrast, in the humid climate of western New York (Wyoming county), Equation 2 predicts substantial losses, while the temperature-based method does not predict any loss. Finally, and perhaps most significantly, those regions that are currently experiencing the greatest losses are also the most susceptible to additional losses: they are projected to be impacted the most by climate change. The above differences stem not only from the non-linearity of the response curve to temperature, all else equal, but also from the sensitivity to humidity, and from subtle differences relating to the varying impacts of minimum and maximum THI on the estimated loss.

Production losses across the United States

The spatial structure in mean summer conditions is shown in Figure 4, which includes maps of the mean summer (June-Aug) maximum temperature and afternoon humidity for the period 1950-1999. The pattern in maximum temperature is primarily modulated by latitude, elevation, and proximity to coasts, with a notable maximum in the U.S. Southwest. The spatial pattern in humidity, in contrast, shows a localized maximum along the coasts and a broad East-West contrast that is roughly delineated by the eastern edge of the U.S. Great Plains.

The complex patterns of humidity and temperature are reflected in the estimate of lost milk production per cow for the historical period (Figure 5). We see, for example, the dominance of high temperatures in Arizona as well as the increased sensitivities resulting from the high humidities found in the Southeast. Also apparent is that many of the regions that are currently strong in dairy production (see Figure 1) are located in areas with relatively mild summer climates, where the impacts of heat stress are relatively small. This is not universally true, however, as exemplified by the milk-producing regions in central California, Arizona, and Florida, where the impacts of heat stress can be quite severe.

The top panel of Figure 6 shows the projected changes in summertime temperature for the 2050s relative to the historical period. Note that the projected temperature changes vary smoothly across the domain, a result of the low resolution of the global models, with substantially higher warming throughout the interior than along the coasts As described above, these changes in temperature were applied to the higher-resolution historical record to estimate future losses in milk production. The bottom panel of Figure 6 shows the difference in mean daily milk loss per cow for the 2050s relative to historical. The pattern of changes in lost production is quite different than the pattern of changes in temperature, a result of both the high-resolution meteorological data and the non-linearity of the dependence on temperature and humidity. For example, despite relatively low warming over Florida (Fig 6a), substantial production losses are projected (Fig 6b) due to the high temperature sensitivity of this humid region (Fig 2). Although not shown, results for the 2080s are qualitatively similar to those shown for the 2050s, and are summarized in Tables 1 and 2 and in the supplementary material.

The data show that there are few parts of the country that are both amenable to dairy farming (e.g., adequate supply of water and feed, topographically suitable) and unaffected by climate change. Furthermore, future changes in climate are projected to accentuate regional disparities, with the areas that are already experiencing greater losses per cow—Arizona, the San Joaquin Valley in California, much of the Southeast, and the southern Midwest states—facing the most severe additional losses.

Economic impacts

Table 1 shows our estimates of milk production losses for ten selected counties; similar data for 2,801 counties in the conterminous United States are included in the online supplement, plus totals for the conterminous U.S. as a whole and for each of the lower 48 states (see note 2 below). A weighted average for the entire U.S. (shown in Table 2, along with results for selected states) yields a per-cow loss of 0.57 kg/day for the historical period, 1.42 kg/day for the 2050s, and 1.88 kg/day for the 2080s. Using 30 kg/day as a baseline for production without any heat stress, loss per-cow rises from 1.9% of the baseline for the historical period to 4.7% for the 2050s and 6.3% for the 2080s. This corresponds to economic losses for the country as a whole of

$666m/year in the historical period, $1.66b/year in the 2050s, and $2.21b/year in the 2080s. SP2003 estimated that optimal heat abatement can reduce losses by 29%. Applying this reduction to our figures yields ballpark estimates of losses with optimal heat abatement of $473m/year for the historical period, rising to $1.18b/year for the 2050s and $1.57b for the 2080s. When interpreting these numbers it is important to note that they are based on the annual average in production loss, whereas the vast majority of the impacts are felt during the summer season (see Figure 2). As a consequence, daily production losses in June through September are approximately triple those quoted above (i.e., historical production losses for June-Sept are approximately 1.71 kg/day, or 5.7%). Concentrating such losses in one season could have more significant impacts than the annually averaged numbers imply, for example by limiting cash flow and therefore posing a risk to operations.

Conclusions

The primary objective of this paper is to establish the important climatic considerations in assessing climate impacts on dairy production. We compute losses using high-resolution (1/8º) gridded temperature and humidity data. Future losses are based on projected temperatures for mid-century (2050s) and late-century (2080s) taken from a composite of all 16 archived CMIP3 climate model simulations. We apply this data to a recent, comprehensive analysis of the empirical relationship between heat stress and milk production losses in U.S. Holstein dairy cows (SP2003). By employing both an improved representation of impacts to dairy production and a well-tested, highly-resolved climatic dataset, our assessment of climate change impacts can account for localized variation in production losses and thus provide a more precise estimate of climate impacts both historically and in the future.

We find that production losses are strongly influenced by geographic, seasonal, and diurnal variations in humidity and temperature. In all but the most temperate regions, 21st century warming is projected to result in increased production losses as well as an increase in the number of days when cows experience heat stress. Climate change is likely to exacerbate regional disparities, making milk production even more difficult in the Southeast U.S. and other areas that are already experiencing relatively large climate-related limitations on milk production. Perhaps not surprisingly, we also find that cows within each region are generally raised in more temperate areas where losses related to heat stress are lower relative to the surrounding regions. As a result the U.S. dairy industry as a whole is less vulnerable to climate change than one might infer without geographically resolved data.

Combining our estimated production loss per cow with county-level dairy populations, we obtain estimates of economic losses at the county level for the entire conterminous United States. We estimate that annual losses due to heat stress (at current prices, and without any heat abatement activity) could more than triple, exceeding \$2b by the end of the 21st century. These losses are concentrated in the summer season. Although localized impacts of heat stress can be quite severe and nationwide losses in excess of \$2 billion per year should not be ignored, it is worth emphasizing that, relative to baseline production, climate change is only projected to reduce nationwide dairy production by 6.3% by the 2080s. Our results thus indicate that the impacts of climate change on nationwide milk production will be measurable, but modest.

Notes

1. Gridded humidity data are not available at daily time steps: the use of monthly data is necessitated by the sparsity of surface humidity observations, which are much less common than observations of temperature.

2. Milk loss per cow is a weighted average of county-level data based on dairy population; state totals reflect all cows in each state but county-specific populations were not available for all counties, so “unattributed” cows—a percentage ranging from 1% in California, Wisconsin, and New York to 28% in Florida—were allocated to the “unattributed” county with the smallest amount of milk loss per cow. This makes our estimates more conservative, but in general does not strongly affect our estimates.

References

Ahmed, MMM and El Amin, AI (1997). *Effect of hot dry summer tropical climate on forage intake and milk yield in Holstein–Friesian and indigenous zebu cows in Sudan*. Journal of Arid Environments 35: 737–745.

Daly, C., W. P. Gibson, G.H. Taylor, G. L. Johnson, P. Pasteris (2002). *A knowledge-based approach to the statistical mapping of climate.* Climate Research, 22: 99-113.

Hahn GL (1999). *Dynamic Responses of Cattle to Thermal Heat Loads*. Journal of Animal Science 77:10-20.

Hamada T (1971). *Estimation of lower critical temperatures for dry and lactating cows.* J. Dairy Sci., 54, 1704-1705.

Hatfield JL, Boote KJ, Fay PA, Hahn GL, Izaurralde RC, Kimball BA, Mader TL, Morgan JA, Ort DR, Polley HW, Thomson AM, Wolfe DW (2008). *Agriculture*. In: The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.

Hayhoe, K, et al (2004). *Emissions pathways, climate change, and impacts on California*. PNAS 110:12422–12427.

Kadzere, CT, Murphy MR, Silanikove N, Maltz E (2002). *Heat stress in lactating dairy cows: a review.* Livestock Production Science, 77:59-91.

Klinedinst PL, Wilhite DA, Hahn GL, Hubbard KG (1993). *The potential effects of climate change on summer season dairy cattle milk production and reproduction*. Climatic Change 23: 21-36.

Mader TL, Frank KL, Harrington JA, Hahn GL, Nienaber JA (2009). *Potential climate change effects on warm-season livestock production in the Great Plains.* Climatic Change 97:529–541.

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy (2007), *Fine-resolution climate projections enhance regional climate change impact studies.* Eos Trans. AGU, 88(47), 504.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen (2002). *A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States*. *J. Climate* 15(22), 3237-3251

Nakicenovic, N et al. (2000). *Special Report on Emissions Scenarios:* A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. http://www.grida.no/climate/ipcc/emission/index.htm

Ravagnolo O and Misztal I (2000). *Genetic component of heat stress in dairy cattle, parameter estimation.* J. Dairy Sci. 83:2126–2130.

Ravagnolo O, Misztal I, and Hoogenboom G (2000). *Genetic component of heat stress in cattle, development of heat index function.* J. Dairy Sci. 83:2120–2125.

Shepard, D.S (1984). *Computer mapping: the SYMAP interpolation algorithm.* In: Spatial Statistics and Models, Gaile, G.L. and Willmott, C.J., eds. Dordrecht, Netherlands: D. Reidel Publishing Company, pp. 133-145

St-Pierre NR, Cobanov B, Schnitkey G (2003). *Economic Losses from Heat Stress by US Livestock Industries*. Journal of Dairy Science 86: E52–E77.

USDA (2012). *Economic Research Service: Milk cows and production by State and region (Annual)*. http://www.ers.usda.gov/datafiles/Dairy_Data/milkcowsandprod_1_.xls. Accessed February, 2012.

USDA (2011a). *Milk: Production per Cow by Year, US.* National Agricultural Statistics Service Charts and Maps. http://www.nass.usda.gov/Charts_and_Maps/. Accessed June 27, 2011.

USDA (2011b). National Agricultural Statistics Service Quick Stats, http://www.nass.usda.gov/. Accessed June 27, 2011.

USDA (2010). *USDA Agricultural Projections to 2019, Long-term projections report OCE-2010-1.* http://www.ers.usda.gov/publications/oce101/.

West JW (2003). *Effects of Heat-Stress on Production in Dairy Cattle.* Journal of Dairy Science 86:2131–2144.

West JW, Mullinix BG, Bernard JK (2003). *Effects of Hot, Humid Weather on Milk Temperature, Dry Matter Intake, and Milk Yield of Lactating Dairy Cows.* Journal of Dairy Science 86:232–242.

Tables

				Milk loss per cow (kg/day)			Economic loss ($m/year)		
County	**Lat.**	**Long.**	**Milk cows, 1000s**	**1950-99**	**2050s**	**2080s**	**1950-99**	**2050s**	**2080s**
Chaves, NM	33.36	-104.44	94	-0.75	-1.90	-2.51	-$9.0	-$22.8	-$30.2
Clark, WI	42.65	-90.76	64	-0.14	-0.59	-0.89	-$1.1	-$4.8	-$7.2
Lancaster, PA	40.07	-76.28	97	-0.44	-1.35	-1.88	-$5.5	-$16.7	-$23.3
Maricopa, AZ	33.49	-112.09	100	-3.09	-5.43	-6.34	-$39.4	-$69.3	-$81.0
Okeechobee, FL	27.27	-80.85	25	-3.91	-6.68	-8.01	-$12.5	-$21.3	-$25.6
Tillamook, OR	45.48	-123.78	26	-0.01	-0.03	-0.05	-$0.0	-$0.1	-$0.2
Tulare, CA	36.23	-119.17	482	-0.56	-1.29	-1.67	-$34.6	-$79.3	-$102.9
Weld, CO	40.43	-104.62	73	-0.22	-0.73	-1.02	-$2.0	-$6.8	-$9.5
Wyoming, NY	42.65	-78.20	48	-0.08	-0.37	-0.62	-$0.5	-$2.3	-$3.8
Yakima, WA	46.48	-120.51	87	-0.10	-0.33	-0.48	-$1.2	-$3.7	-$5.4

Table 1: Milk loss per cow (kg/day) and total economic loss ($m/year) for 10 U.S. counties.

		Milk loss per cow (kg/day)			Economic loss ($m/year)		
State	**Milk cows**	**1950-99**	**2050s**	**2080s**	**1950-99**	**2050s**	**2080s**
California	1,840,000	-0.85	-1.82	-2.31	-200	-427	-543
Texas	430,000	-1.45	-3.25	-4.11	-79	-178	-226
Wisconsin	1,255,000	-0.21	-0.81	-1.19	-33	-130	-190
Arizona	190,000	-2.56	-4.62	-5.45	-62	-112	-132
Florida	118,000	-3.43	-6.19	-7.46	-52	-93	-112
Pennsylvania	550,000	-0.27	-0.89	-1.30	-19	-63	-91
New Mexico	336,000	-0.57	-1.49	-2.00	-24	-64	-86
Minnesota	468,000	-0.24	-0.96	-1.27	-14	-52	-76
New York	625,000	-0.12	-0.49	-0.78	-10	-39	-62
Ohio	276,000	-0.34	-1.19	-1.71	-12	-42	-60
U.S. total	9,169,824	-0.57	-1.42	-1.88	-666	-1,663	-2,206

Table 2: As in Table 1, except applied to the ten most-impacted states and the U.S. as a whole (see note 2 above)

Figure Captions

Figure 1. Distribution of dairy cows in the conterminous U.S., by county. Data from USDA (2011b).

Figure 2. Dairy production loss (calculated from Equation 2), shown as a function of daily-average temperature for several locations. Arrows pointing down and up (respectively) compare the observations from Ahmed and El Amin (1997) and the reproduction of those losses calculated using the THI method (Equation 2) with a baseline milk production of 30 kg/day in the absence of heat stress. The black lines represent losses based on the 1.15 kg/°C sensitivity used in Hayhoe et al. (2004) for both the 25°C and 32°C thresholds.

Figure 3. Annual cycle of milk loss (kg/day) for selected counties for the historical period (1950-1999) and projections for the 2050s.

Figure 4. Mean summer (Jun-Aug) climate for the conterminous United States. Summer, rather than annual, averages of temperature and humidity are shown since the bulk of dairy production losses occur during this season (See Figure 3 and associated discussion for details).

Figure 5. Annual historical (1950-1999) milk production losses.

Figure 6. Projected changes in temperature and milk production for the 2050s relative to historical. Temperature changes were obtained for the A1B emissions scenario from an ensemble average of global climate model (GCM) simulations. Note that the smooth, broad-scale temperature projections are a result of the low resolution GCMs. The loss projections show much more fine-scale structure, due to both the highly-resolved historical temperature and humidity data (Figure 4) and their non-linear relationship with production losses (Equation 2).

Figures

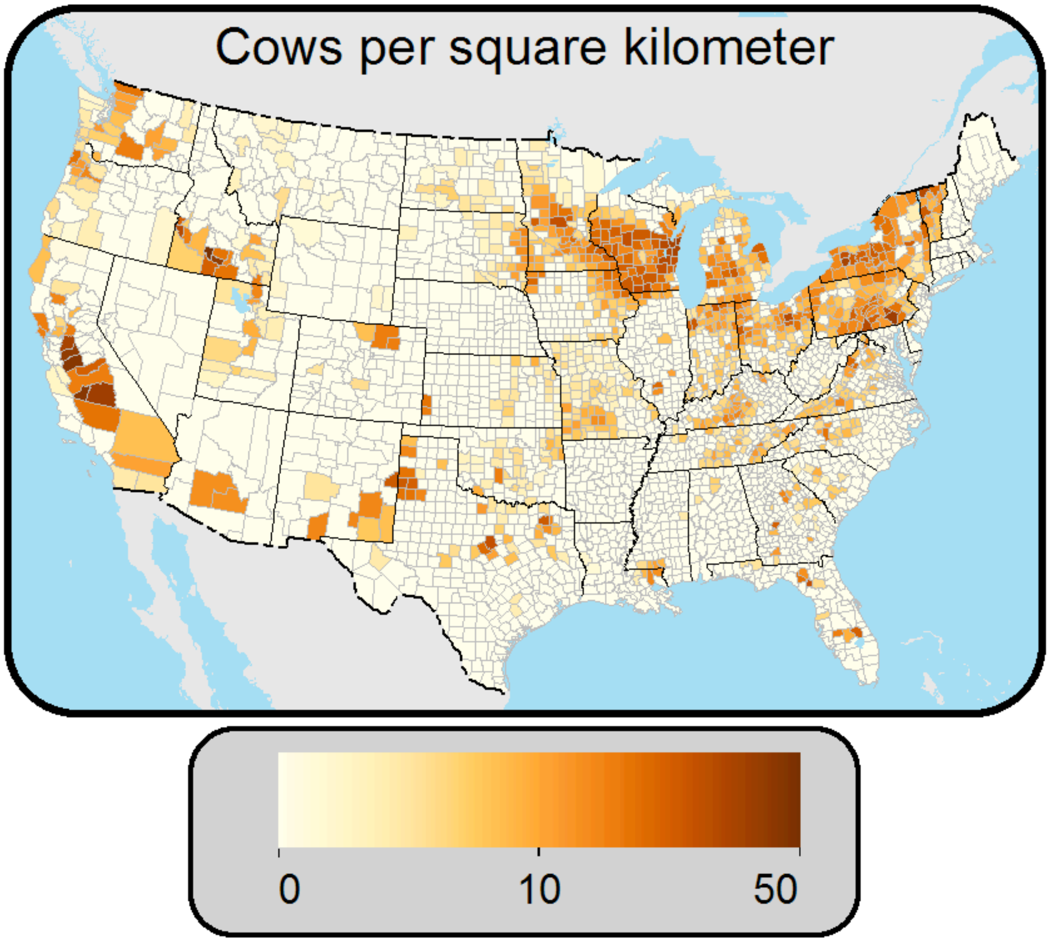

Figure 1

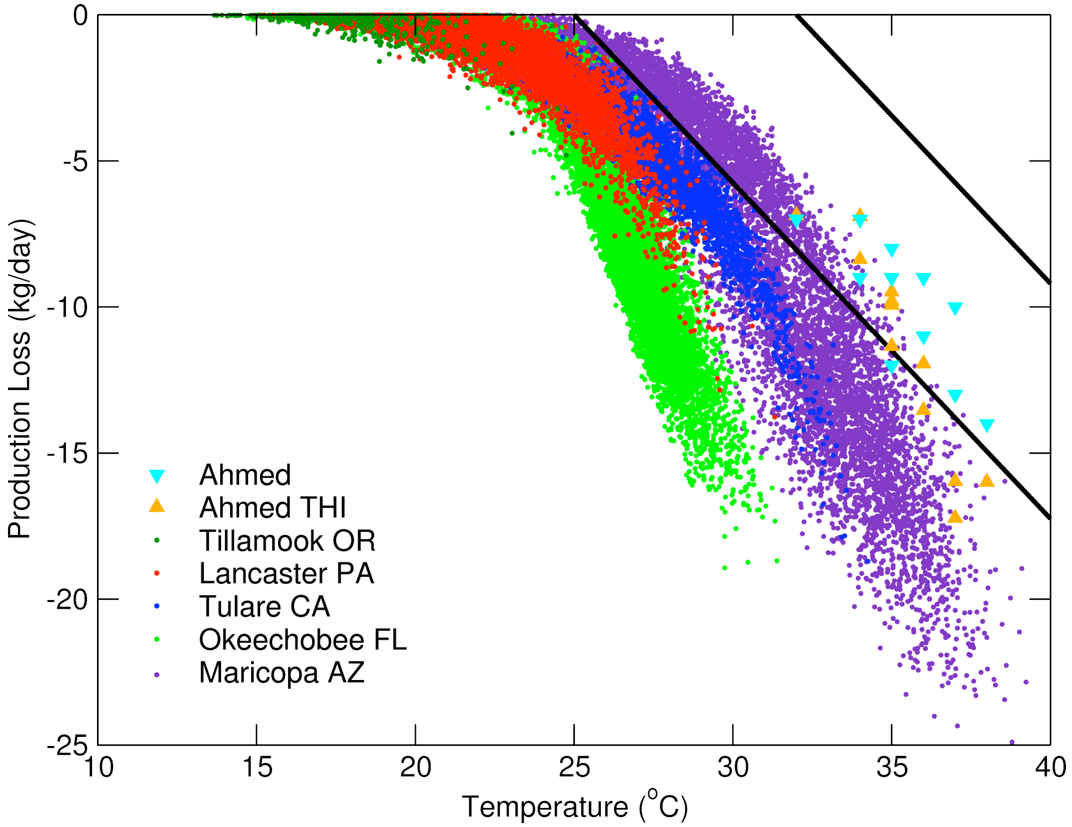
0
-5
-10
-15
-20
-25
10
15
20
25
30
35
40
Production Loss (kg/day)
Temperature (°C)
Ahmed
Ahmed THI
Tillamook OR
Lancaster PA
Tulare CA
Okeechobee FL
Maricopa AZ

Figure 2

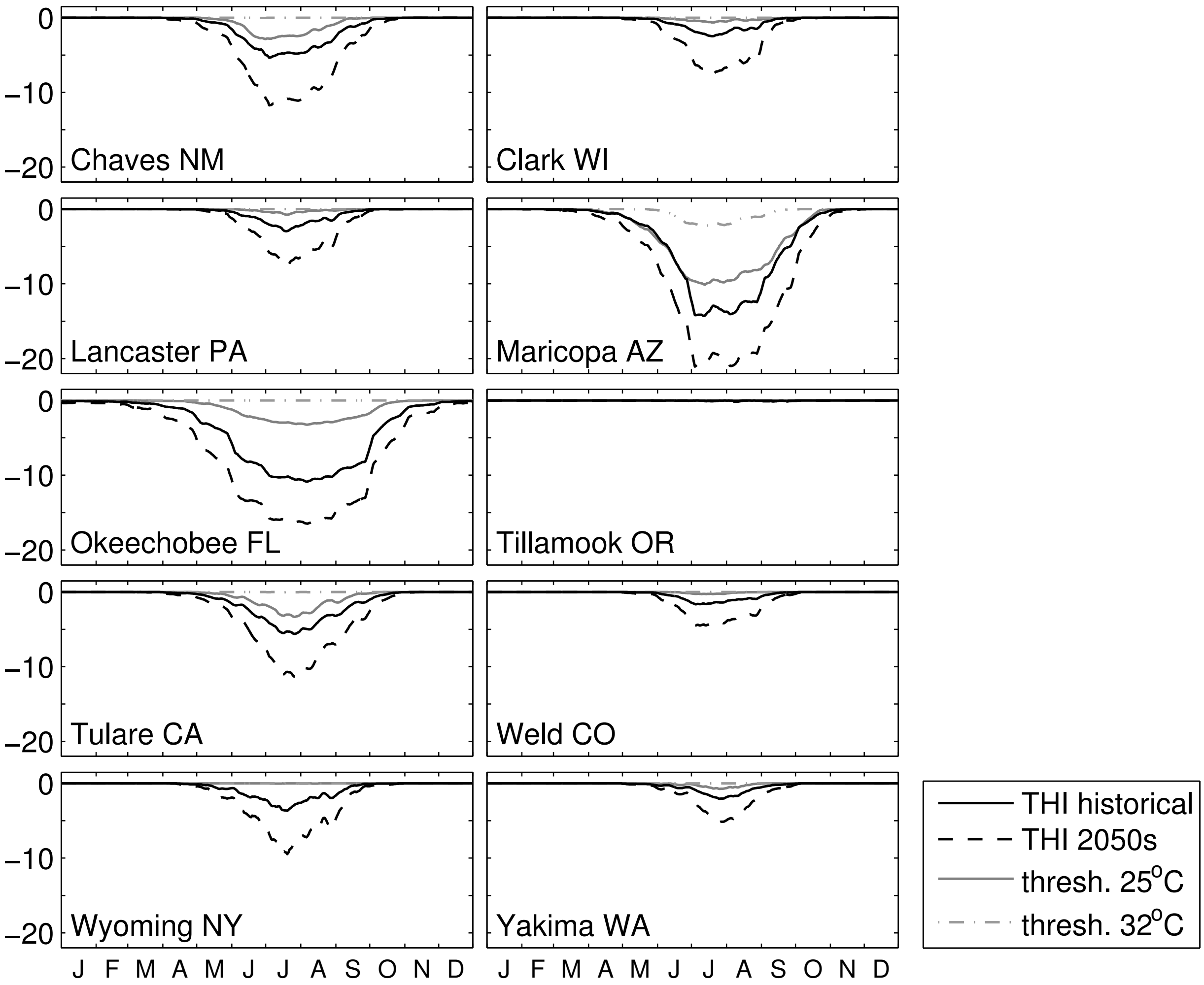
0
−10
−20
Chaves NM
Clark WI
Lancaster PA
Maricopa AZ
Okeechobee FL
Tillamook OR
Tulare CA
Weld CO
Wyoming NY
Yakima WA
J F M A M J J A S O N D
THI historical
THI 2050s
thresh. 25^{o}C
thresh. 32^{o}C

Figure 3

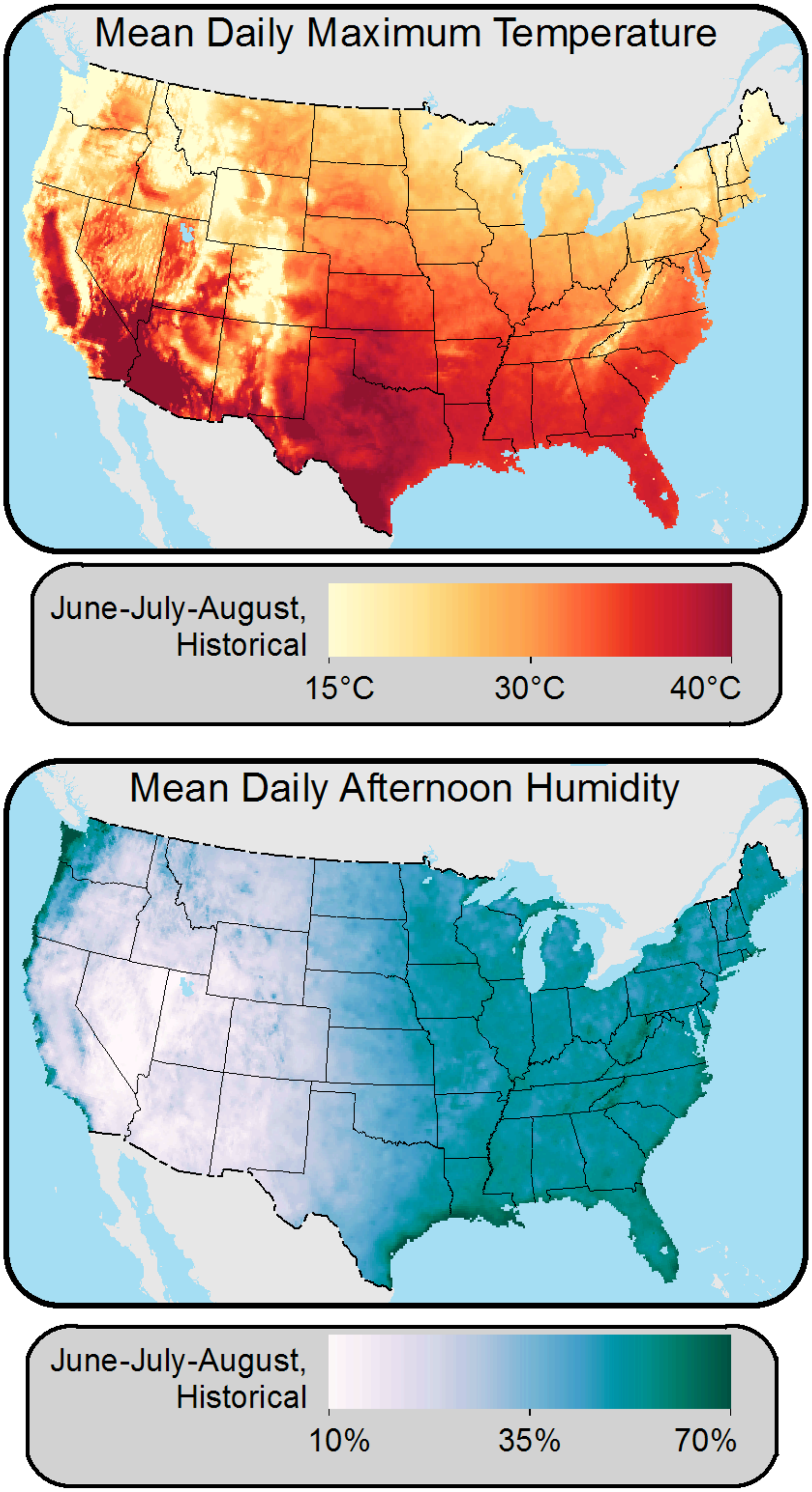
Mean Daily Maximum Temperature
June-July-August,
Historical
15°C
30°C
40°C
Mean Daily Afternoon Humidity
June-July-August,
Historical
10%
35%
70%

Figure 4

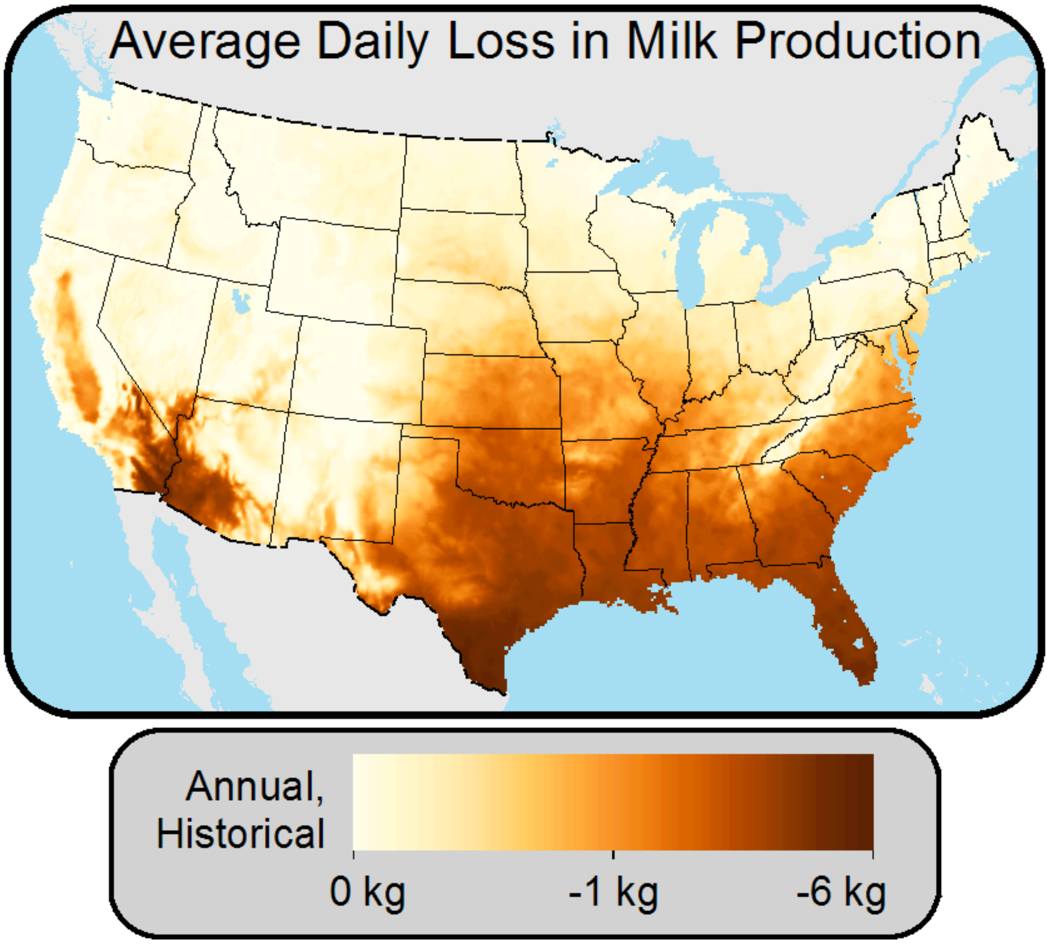
Average Daily Loss in Milk Production
Annual,
Historical
0 kg
-1 kg
-6 kg

Figure 5

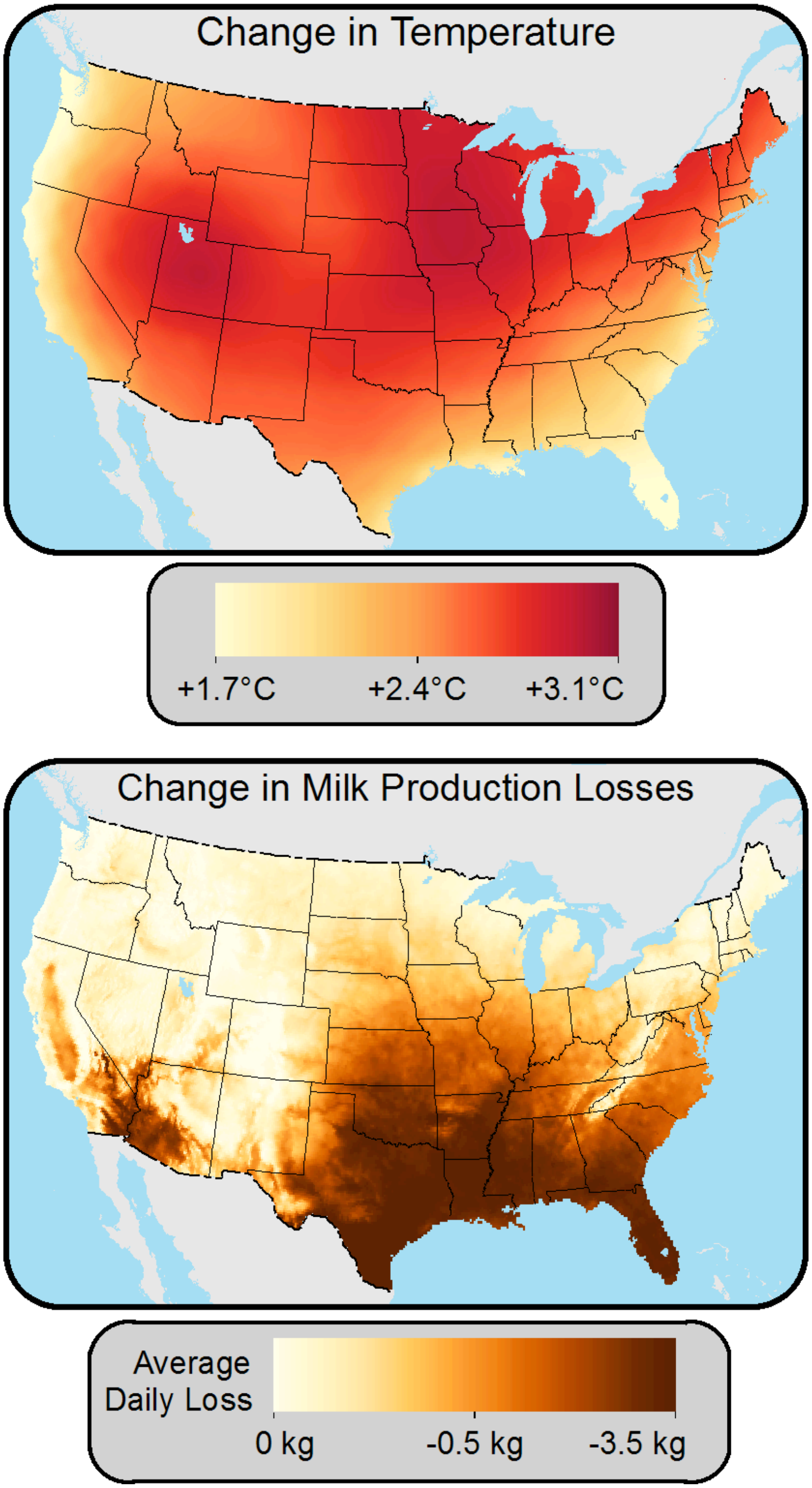
Change in Temperature
+1.7°C
+2.4°C
+3.1°C
Change in Milk Production Losses
Average Daily Loss
0 kg
-0.5 kg
-3.5 kg

Figure 6