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**The Potential Effects of Climate Change  
on the Productivity, Costs, and Returns  
of U.S. Dairy Production**

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and  
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**Abstract:**

Climate change could affect the costs and returns of livestock production by altering the thermal environment of animals thereby affecting animal health, reproduction, and the efficiency by which livestock convert feed into retained products (especially meat and milk). In the United States, concentrated livestock operations are located in a variety of climatic regions, suggesting that the industry could adapt to future changes in temperature and weather patterns resulting from global warming. However, this adaption could be costly. We use nationally representative data on dairy producers coupled with finely-scaled climate data to empirically examine how producers' costs, returns, and production systems vary across U.S. regions as a function of the local climate.

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Global climate change is expected to alter temperature, precipitation, atmospheric carbon dioxide levels, and water availability in ways that will affect the productivity of crop and livestock systems (Hatfield, et al. 2008). For livestock systems, climate change could affect the costs and returns of production by altering the thermal environment of animals thereby affecting animal health, reproduction, and the efficiency by which livestock convert feed into retained products (especially meat and milk). In the United States, concentrated livestock operations are located in a variety of climatic regions, suggesting that the industry could adapt to future changes in temperature and weather patterns resulting from global warming. However, this adaptation could be costly. Climatic changes could increase thermal stress for animals and thereby reduce animal production and profitability by lowering feed efficiency, milk production, and reproduction rates (Fuquay, 1981; Morrison 1983; St-Pierre, Cobanov and Schnitkey, 2003). Methods that livestock producers use to mitigate thermal stress – including modifications to animal management or housing –tend to increase their production costs.

Past research on climate's effects on livestock production largely uses engineering models to predict how productivity may decline with higher temperatures. Very few studies address climate mitigation costs, and those that do usually account for these costs based on predictive models rather than survey evidence of actual behavior.

In this article we take a very different approach and use nationally representative data on dairy producers coupled with finely-scaled climate data to empirically examine how producers' costs, returns, and production systems vary across U.S. regions as a function of the local climate. This analysis is a preliminary step towards comprehending how the livestock industry has adapted to regional variations in climate, and eventually to understanding the costs of adaptation to possible future climate changes.

## **Background**

There is a substantial scientific literature examining the relationship between climatic characteristics (temperature, humidity, wind speed, etc.) and animal productivity (NRC, 1981). Fundamental to much of this literature is the concept of the thermoneutral zone – the optimal range of temperatures and environmental conditions in which the animals do not need to alter behavior or physiological function to maintain a normal body temperature.

At temperatures below the thermoneutral zone, livestock generally expend more energy and increase their voluntary feed intake in order to maintain their core temperature, resulting in lower feed efficiency (NRC, 1981). Maintaining an adequate temperature can be an important factor influencing design of housing and in husbandry decisions for cold susceptible animals such as poultry, swine, and young animals. Low temperatures resulting from particularly cold weather or loss of power to buildings housing confined animals, can cause economic losses from increased animal morbidity or death (Mader 2003).

Above the thermoneutral zone, animals may experience heat stress and respond by reducing their voluntary feed intake, which reduces their weight gain and feed efficiency (Hahn, 1999; NRC, 1981; West, 1994; Cooper and Washburn, 1998; Yalcin et al. 2001). Heat stress can also reduce fertility, milk production, and reproduction (Hansen et al. 2001, Drost et al, 1999; Renaudeau and Noblet, 2001 ). Extended periods of high temperature can be lethal for livestock, and a particular risk for feedlot cattle in some regions (Hahn et al 1999; Hahn and Mader 1997).

Global warming is likely to increase temperature levels and the frequency of extreme temperatures – hotter daily maximums and more frequent or longer heat waves – which could adversely affect livestock production in the warm season. In some regions, economic losses due

to warmer temperatures in the summer may be offset by greater productivity in the winter (Hatfield, et al. 2008).

A limited number of studies have used agricultural engineering models of the relationship between climatic conditions and feed intake to estimate the effects of climate change on the performance of domestic animals. Frank et al. (2001) use a model relating climate to feed intake and weight gain and milk production to estimate the response of dairy cows to predicted climate changes in the Great Plains region. The study estimated reductions in milk production of 5.1% to 6.8% by 2090 in the absence of efforts to mitigate the effects of temperature changes (e.g. by using evaporative cooling in barns).

Using a broadly similar approach, St-Pierre, Cobanov and Schmitkey (2003) estimate the economic losses attributable to heat stress by all major US livestock industries. The authors did not simulate the effects of global warming climate scenarios, but instead compared animal performance, reproduction and mortality under current conditions to a hypothetical “ideal” climate scenario (in which livestock are in their thermoneutral zone). The authors find that heat stress has an economic cost of between \$1.69 and \$2.36 billion dollars, with approximately 40-60% of these costs occurring in the dairy sector, and the remainder in the beef, swine, and poultry industries. Using cost parameters drawn from the agricultural engineering literature, the authors also estimated the optimal level of expenditures on heat mitigation efforts.

### **Conceptual framework**

Climate can affect profits by altering the productivity of inputs – for example, outside of the thermoneutral zone animals gain less weight holding inputs constant. Producers mitigate this productivity loss by increasing expenditures on capital (buildings/cooling systems), energy (to

operate cooling systems), and perhaps adjust other inputs, such as feed. While climate may be an important factor in determining agricultural output and productivity, the existence of many other factors (input prices, output prices, and other costs) may outweigh climate in determining an operations location. Consequently, farms may be observed in a variety of climatic regions.

To illustrate how climate is related to input use and profits, let livestock production be described by:

$$(1) \quad y_i = f(x_i, c_i, z_i; \beta),$$

where  $y_i$  is output (e.g., cwt of milk, cwt gain, cwt of broiler) of operation  $i$ , which is a function of inputs  $x_i$ , a single climate variable  $c_i$ , and other exogenous factors  $z_i$  thought to influence productivity, and parameters  $\beta$ . Profit maximizing farmers are assumed to choose input levels to maximize profits, which are given by:

$$(2) \quad \pi_i = p_i f(x_i, c_i, z_i; \beta) - \sum_j w_{ji} x_{ji},$$

where  $p_i$  is the output price and  $w_{ji}$  is the price of input  $j$ .

Consider two identical operations located in different climate regions: one in a region with a favorable climate for livestock  $c^L$  and a second located in a warmer climate  $c^H$ , where the temperature often exceeds the animal's thermoneutral zone (figure 1). The curve  $\pi(\bar{x}, c, w_H)$  shows the profits that can be earned if operators made no input adjustment for climate – that is, if inputs are held constant at  $\bar{x}$ . In this case, operators earn lower profits in the warm region compared to the cool region ( $\pi_0^H < \pi_0^L$ ), perhaps because heat stress reduces livestock weight gain.

The curve  $\pi(x, c, w_0)$  describes profits if operators can adjust inputs (e.g., buildings, cooling equipment, energy) to account for the climate. In this case, adjusting inputs raises profits for the operation in the warm region. However, profits earned in the warm region are still lower

than in the cooler region because of the additional input expenditures incurred, i.e.,  $\pi_0^L > \pi_1^H > \pi_0^H$ . Hence, the effect of a change in the climate from  $c^L$  to  $c^H$  on profits, holding prices and technology constant, is:  $\pi_0^L - \pi_1^H$ .

Now consider a situation with lower input prices ( $w_1 < w_0$ ) where profits are described by the curve  $\pi(x, c, w_1)$  in figure 1. If prices are only lower in the warmer region, then for the case shown a farmer could earn higher profits in the warm region compared to the cooler region ( $\pi_2^H > \pi_0^L$ ) despite the efficiency loss caused by being in a warmer climate (the same results could apply if output prices were higher in the warmer region). Note that the effect of a change in climate (from  $c^L$  to  $c^H$ ) on profits is still  $\pi_0^L - \pi_1^H$ . Hence, summary statistics comparing profits earned in different climate regions may not reveal the effect of climate unless we control for differences in prices and technologies.

Figure 2 illustrates the relationship between climate and input use and expenditures. Let the input demand curve  $x^*(c, w_0)$  describes the optimal quantity of an input that is used to mitigate the effects of climate - such as energy to power cooling equipment. The curve  $w_0 x^*(c, w_0)$  describes input expenditures at the optimal input levels.

As before, consider two operations located in different climates. If both operations face the same energy price  $w_0$ , then input demand is greater for the operation in the warm climate ( $x_0^H > x_0^L$ ) because the operation can increase profits by using more energy to mitigate the negative effects of climate. As shown in figure 1, the higher input demand and higher input expenditures ( $w_0 x_0^H > w_0 x_0^L$ ) in the warm region cause profits to be lower in the warm region.

Now consider the case where energy prices are lower in the warm region ( $w_1 < w_0$ ). In this case, the operation in the warm region would demand more energy ( $x_1^H > x_0^H$ ) than if energy prices were higher. However, with lower energy prices, greater demand for electricity does not

necessarily imply higher energy expenditures. For the example shown in the figure, the operation in the warm region spends less on energy than the operation in the cooler region ( $w_1 x_1^H < w_0 x_0^L$ ), and could earn higher profits, as was shown in figure 1. Hence, a comparison of inputs or input expenditures by operations in different climate regions may not reveal the effect of climate unless we control for differences in prices and technologies.

### **Empirical Approach**

In this article we describe how specific dairy costs, practices, and outcomes relate to climate. However, many of these will also vary with size of operation. If operation size and the outcome variables are both correlated with climate, we may be unable to distinguish between their individual effects in graphical descriptions. To attempt to control for the effects of farm size on the outcome variables of interest, we show in our graphical analysis the value of the variables “de-meant” for operation size. This involves first estimating a relationship between the variable of interest ( $z$ ) and operations size ( $m$ ). To do this in a parametric fashion, we estimate values of  $z$  ( $\hat{z}$ ) as a function of  $m$  and estimated parameters  $\hat{\beta}$ :

$$(3) \quad \hat{z} = f(m; \hat{\beta})$$

We then calculate the residual  $z_{resid} = z - \hat{z}$ . In our graphical analyses we show the relationship between  $z_{resid}$  and the climate variable  $c$ . A parametric way of describing this relationship is:

$$(4) \quad \hat{z}_{resid} = g(c; \hat{\gamma}).$$

Equations (3) and (4) describe parametric relationships between variables, which we present for expository purposes. However, to allow for more flexibility in functional form, in



practice we estimate the predicted values of  $\hat{z}$  and  $\hat{z}_{resid}$  using non-parametric techniques. Specifically, we use local linear regressions with a triangle kernel.

In practice, we find the mean of  $\hat{z}_{resid}$  for 500-unit “bins” of the climate variable (the temperature humidity index load) and plot these points in a scatter diagram. We then fit a local linear regression with a triangle kernel and a bandwidth of 5,000 to these binned averages, and graph the resulting line. This process of binning the residuals and fitting a curve through them can reduce the effect of outliers on the results. However, this process weights each binned average on the graph equally even though each point may represent different numbers of farms.

## **Data**

### *Dairy operation data*

Dairy operation data are drawn from the USDA’s Agricultural Resource Management Survey (ARMS) collected in 2005. The ARMS survey targeted dairy operations in 24 States. The ARMS asks dairy producers about cow inventories and milk production, technology choices, structures and equipment, input use and expenses, and manure management strategies and technologies. It also elicits information on revenues, expenses, production, assets, and liabilities at the whole-farm level, as well as information about the farm operator’s household.

The survey’s information was combined with additional analyses and data to estimate implicit expenses.<sup>2</sup> ERS staff used off-farm wage data from another version of ARMS to estimate the opportunity costs of unpaid labor hours used on the farm. Market price data, from other USDA sources, was used to value the reported quantities of homegrown feed and forages fed to dairy cows. Finally, ERS analysts produced annualized estimates of the cost of replacing

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<sup>2</sup> See MacDonald et al (2007) for more information about the survey (<http://www.ers.usda.gov/publications/err47/err47.pdf>).

the capital used for cattle housing, milking facilities, feed storage structures, manure handling and storage structures, feed handling equipment, tractors, trucks, and purchased dairy herd replacements, plus the interest that the remaining capital could have earned in an alternative use.

### *Climate data*

For information on climate we use the Parameter-elevation Regressions on Independent Slopes Model (PRISM), developed at Oregon State University. PRISM extrapolates between weather stations to generate climate estimates for each 4km grid cell in the U.S. We use the PRISM data on monthly minimum and maximum temperatures, precipitation, and dew point. For more information on PRISM, see <http://www.prism.oregonstate.edu/>.

To match the ARMS data to the PRISM data, we first find the latitude and longitude of the centroid of the zip code of each operation in ARMS. We next use mapping software to find the grid cell of this latitude-longitude point. This grid cell is used as the location for the climate data of each operation.

We utilize climate data from 1990 to 2009; this allows us to calculate not only estimates of the average temperature within the year of the survey (2005), but also averages over the entire 20 year period. For current purposes, we focus on the 20-year average temperature and another indication of heat stress specific to livestock.

Livestock scientists have found that livestock productivity is related to climate through a measure called the Temperature Humidity Index (THI) (St-Pierre, Cobanov and Schnitkey 2003; Chase, undated). THI is calculated as:

$$(3) \quad THI = (\text{dry bulb temperature } ^\circ C) + (0.36 \times \text{dew point temperature } ^\circ C) + 41.2$$

When animals are above a certain THI, productivity (in terms of weight gain, eggs laid, or milk produced) declines. Using our data on minimum and maximum temperatures (dry bulb

temperatures) and the dew point, we generate a minimum and maximum THI for each month and location.<sup>3</sup> Generally, livestock experience heat stress when the THI is above a specific threshold (for dairy this THI is 72).

Following engineering research we estimate a THI load, which refers to the number of hours that the location has a THI above the threshold. To estimate the THI load, we estimate a sine curve between the maximum and minimum THI over a 24-hour period, and then estimate the number of hours above threshold and the degree to which THI is over the threshold (see Fig. 3; the Appendix provides equations for generating this load). We calculate the monthly THI load (assuming that each day in the month experiences the average monthly temperature minimum and maximum, as well as the average dew point). We then total the daily THI loads over the number of days in the month to calculate a monthly THI load. The annual THI load is the sum of the monthly loads.

Examining the frequency of observations in our survey according to the 20-year averages for temperature and THI load shows that dairying occurs in a wide variety of climates. In our sample, dairying occurs in locations with annual average temperatures ranging from 39°F (largely in Idaho, Vermont, and Minnesota) to 74°F (in Florida and Arizona). There is more heterogeneity for dairies according to temperature (Fig. 3) than for THI load (Fig. 4). THI load ranges from zero (for some dairies largely in California, Oregon, and Washington) to nearly 30,000 (with THI loads over 20,000 in Arizona, Florida, and Texas). In our sample, temperature and THI load are fairly linearly related (Fig. 5). States with both low THI loads and temperatures include California, Oregon, and Washington; at the other end of the spectrum, states with both high THI loads and temperatures include Arizona and Florida.

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<sup>3</sup> We only have monthly, not daily data. Our monthly data is the average of the daily data. Thus, the “monthly maximum” is the average over all days’ maxima in the month, not the single greatest temperature in the month.

## Results

We begin by examining the association between dairy operation size and climate to examine whether residualizing our outcome variables is necessary. Fig. 6 shows the relationship between dairy operation size and THI load. To produce this graph, the mean of dairy operation size is taken for 500-unit “bins” of THI load; these are the dots represented on the graph. A local linear regression with a triangle kernel and a bandwidth of 5,000 is then fitted to these binned averages; the curve in the figure represents predictions from this procedure. As is evident, dairy operation size generally increases with increasing THI load.

We next examine use and costs of several dairy production inputs by climate. To adjust for the fact that these variables may vary with size of production, we have “de-meanned” them (as described above). Because there are more observations at the lower THI loads, the binned residual averages are more tightly clustered at lower climates. We first examine the amount of electricity used (Fig. 7). This shows a relatively flat relationship with climate, with an increase in use over a THI load of about 20,000. The highest THI load shows an extremely high electricity use, representing either an outlier or a non-linear effect of climate on electricity use.

In contrast, the cost of feed appears to show a slightly declining relationship with THI load (Fig. 8). We can examine feed costs in more detail by dividing the variable by costs of purchased feed, homegrown feed, and grazed feed. As shown in Fig. 9-11, the cost of purchased feed appears to decline with THI load, while costs for grazing and homegrown feed rise. This suggests that operations are more likely to replace purchased feed with their own feed in hotter climates. This result is somewhat surprising, as one may have expected the opposite to be true.

Heat stress can also lead to animal morbidity and mortality, which can increase costs. We examine veterinary costs and the number of head that died by THI load. While veterinary costs show a great deal of dispersion and no clear pattern according to THI load (Fig.12), the number of head that died shows a non-linear increase, particularly over a THI load of 20,000 (Fig. 13). This exponential relationship between THI load and death accords with engineering predictions (e.g., see St. Pierre, Cobanov, and Schnitkey, 2003).

Certain barn styles are also more prevalent at different climates. Freestall barns, which offer shade and individual (but unrestrained) paddocks for each cow, and which may or may not have walls, are more common in locations with lower THI loads (Fig. 14). Dry lot corrals with “sun shades,” which are open dirt yards with ceiling on poles, do not appear more common in hotter climates (Fig. 15). Looking at a measure of capital costs for housing (Fig. 16), we can see that it declines over climate until the last climate size; the nature of the local linear regression causes the estimated relationship to curve sharply upward based on this “boundary” observation.

Costs of allocated overhead, which include hired labor and unpaid labor costs (Fig. 17), increase with THI load. This may be due to higher per workers costs or more labor used.

We can also examine milk produced according to THI load. Milk produced (Fig. 18) declines with THI load, an expected result based on engineering studies. Despite lower output for dairy at higher THI loads, the gross value of dairy production does not appear to have such a strong relationship (Fig. 19). This may be due to higher dairy prices in warmer regions.

These higher costs and lower outputs at hotter climates do yield somewhat declining net returns by THI load (Fig. 20). However, these lower-than-predicted-for-size net returns are only evident for the highest of THI loads.

## **Conclusions**

For U.S. dairies, this study illustrated how certain measures of productivity, methods of production, and profits vary with climate. We find some evidence that dairy operations located in regions where the humidity adjusted temperature load exceeds a cow's threshold capacity for heat stress for a longer period and greater temperature incur higher costs and have lower productivity than those in cooler regions, even after controlling for a very flexible specification for size.

These preliminary results suggest that future climate changes that increase the THI load in dairy producing regions could affect the U.S. dairy sector – perhaps leading to higher dairy prices and/or altering the location of dairying. However, these graphical analyses are largely exploratory and provide only a descriptive relationship between climate and certain dairy production measures. As we noted in the conceptual framework section, valid comparisons of input levels, expenditures, and profits across climate regions require an adequate control for prices, technologies, and other factors that might be correlated with climate, which we did not do in this analysis. Future work will attempt to estimate an empirical relationship between climate and production that will allow us to predict how future climate change scenarios might affect dairy production.

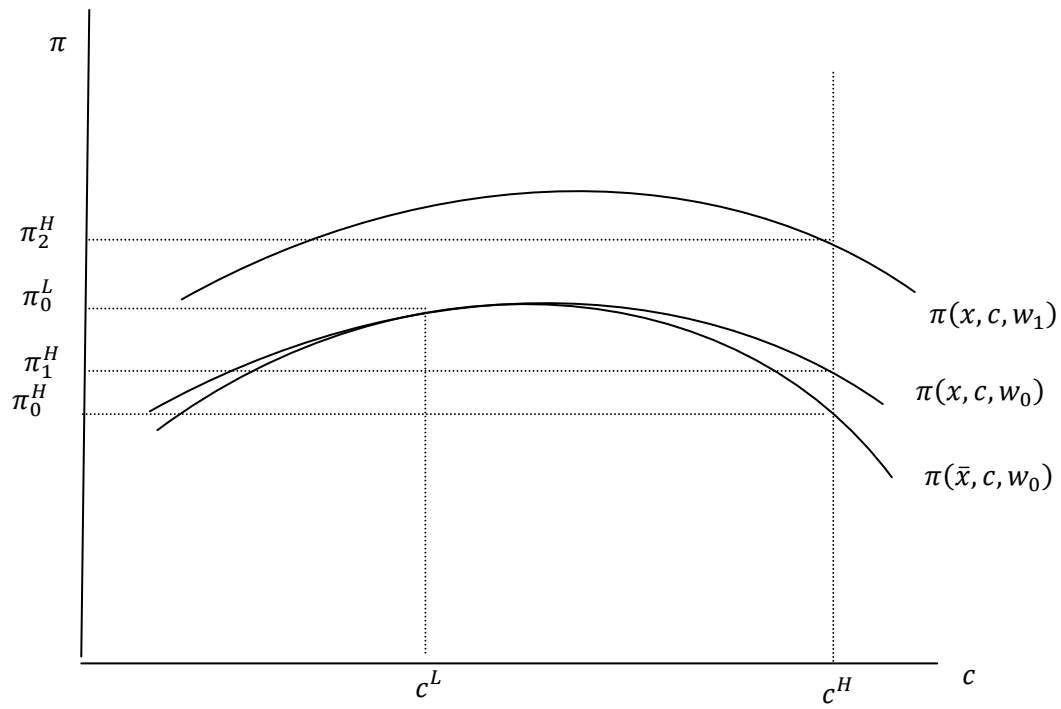
## References

- Cooper, M. A., and K. W. Washburn. (1998) "The relationships of body temperature to weight gain, feed consumption, and feed utilization in broilers under heat stress." *Poultry Science* 77:237–242.
- Drost, M. J., and W. W. Thatcher. (1987) "Heat stress in dairy cows. Its effect on reproduction." *Vet. Clin. North Am. Food Anim. Pract.* 3:609–618.
- Frank, K.L., T.L. Mader, J.A. Harrington, G.L. Hahn, and M.S. Davis, (2001) "Climate change effects on livestock production in the Great Plains." *Proceedings 6th International Livestock Environment Symposium*, American Society of Agricultural Engineers, St. Joseph, MI: 351-358.
- Fuquay, J.W. (1981) "Heat stress as it affects animal production." *Journal of Animal Science*. 52: 164-174.
- Hahn, G.L. (1999) "Dynamic responses of cattle to thermal heat loads." *Journal of Animal Science*, 77, 10-20.
- Hahn, G.L. and T.L. Mader (1997) "Heat waves in relation to thermoregulation, feeding behavior and mortality of feedlot cattle." *Proceedings 5th International Livestock Environment Symposium*, American Society of Agricultural Engineers, St. Joseph, MI: 563-571.
- Hansen, P. J., M. Drost, R. M. Rivera, F. F. Paula-Lopes, Y. M. al-Katanani, C. E. Krininger 3rd and C. C. Chase, Jr. (2001) "Adverse impact of heat stress on embryo production: Causes and strategies for mitigation." *Theriogenology* 55:91–103.
- Hatfield, J., K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, and D. Wolfe. (2008) Agriculture. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, 362 pp
- Fuquay, J. W. (1981) "Heat stress as it affects animal production." *Journal of Animal Science* 52:164–174.
- Mader, T.L. (2003) "Environmental stress in confined beef cattle." *Journal of Animal Science*, 81 (electronic suppl. 2), 110-119.
- Morrison, S. R. (1983) "Ruminant heat stress: effect on production and means of alleviation." *Journal of Animal Science*. 57:1594–1600.
- NRC (National Research Council). (1981) *Effect of Environment on Nutrient Requirements of Domestic Animals*. Committee on Animal Nutrition. Subcommittee on Environmental Stress. National Academy Press, Washington DC.

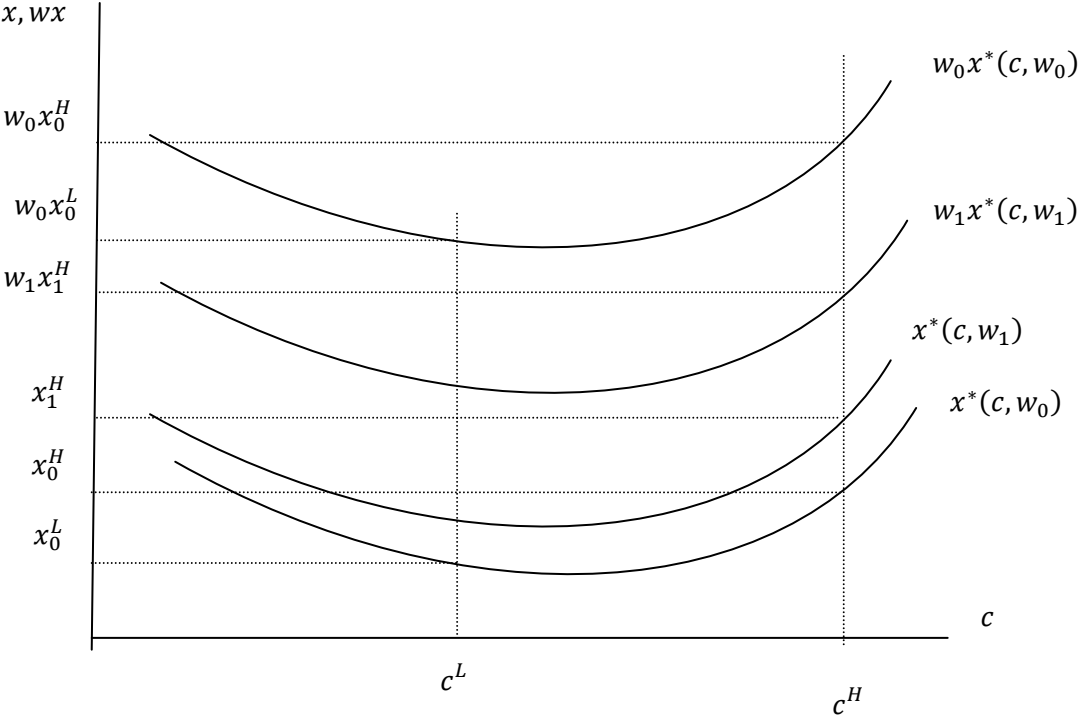
- Renaudeau, D., and J. Noblet. (2001) "Effects of exposure to high ambient temperature and dietary protein level on sow milk production and performance of piglets." *Journal of Animal Science* 79:1540–1548.
- St. Pierre, N.R., B. Cobanov, and G. Schnitkey (2003) "Economic Loss from Heat Stress by US Livestock Industries." *Journal of Dairy Science*. 86(E Suppl.):E52-E77.
- West, J. W. (1994) "Interactions of energy and bovine somatotropin with heat stress." *Journal of Dairy Science*. 77:2091–2102.
- Yalcin, S., S. Ozkan, L. Turkmüt, and P. B. Siegel. (2001) "Responses to heat stress in commercial and local broiler stocks. 1. Performance traits." *Broiler Poultry Science*. 42:149–1



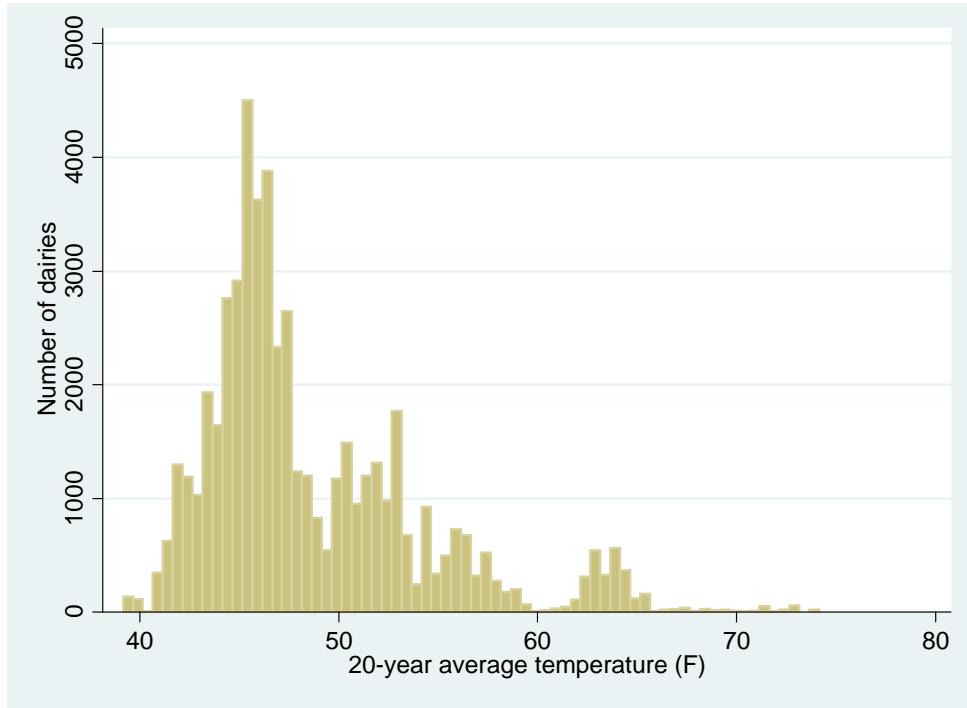
**Figure 1. Profits as a function of climate, with and without input adjustment, and with different input prices**



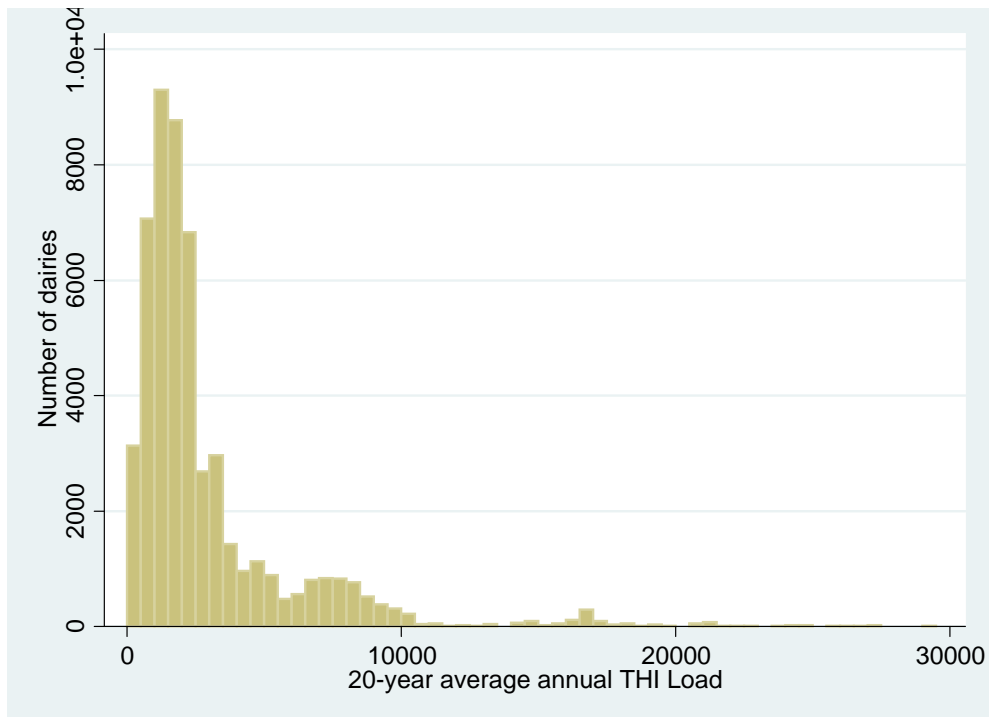
**Figure 2. Demand for, and expenditures on, a climate mitigation input as a function of climate, at different input prices**



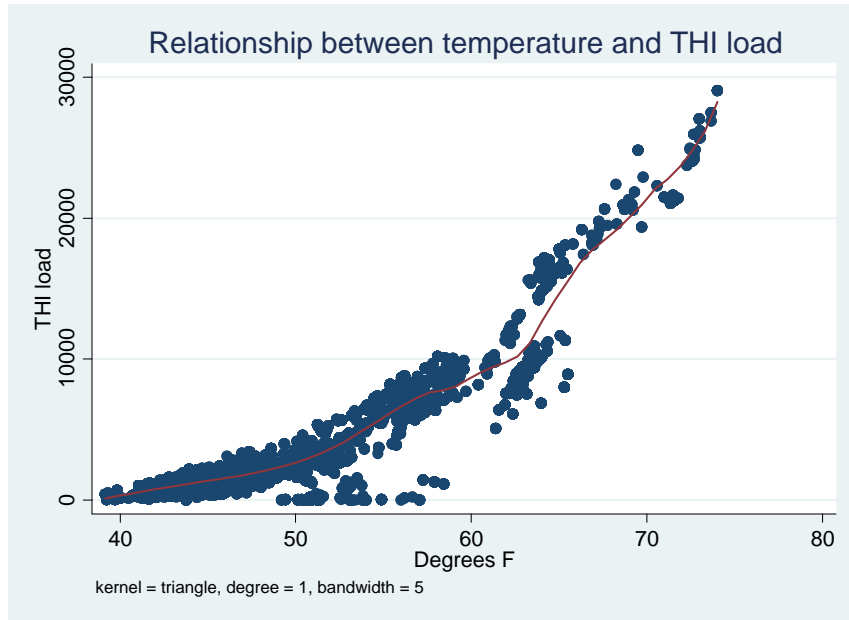
**Fig.3: Frequency distribution of dairies according to 20-year average annual temperature**



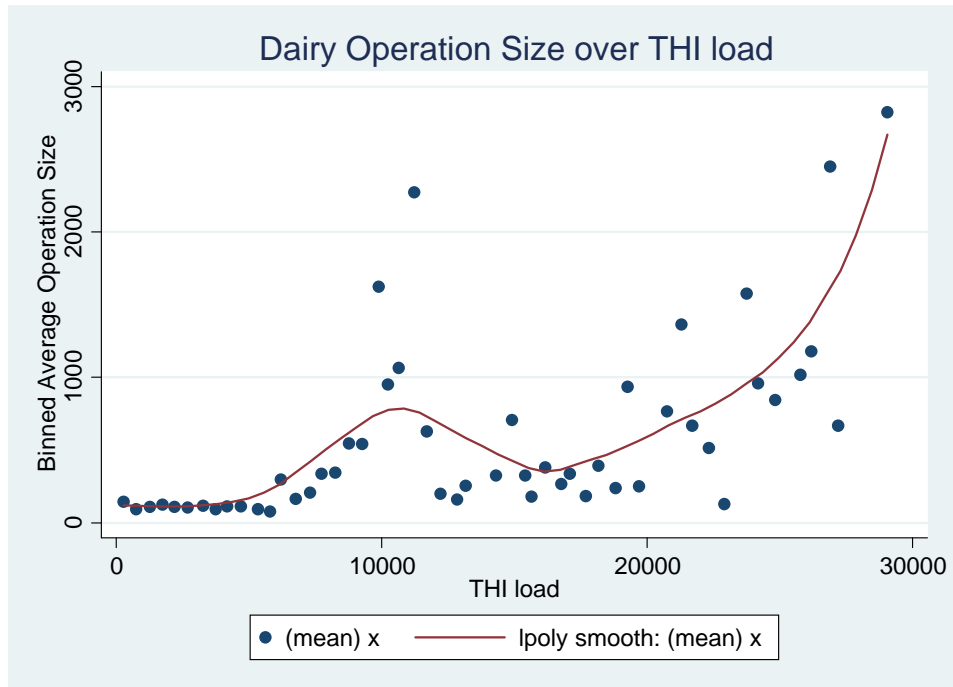
**Fig. 4: Frequency distribution of dairies according to 20-year average annual THI load**



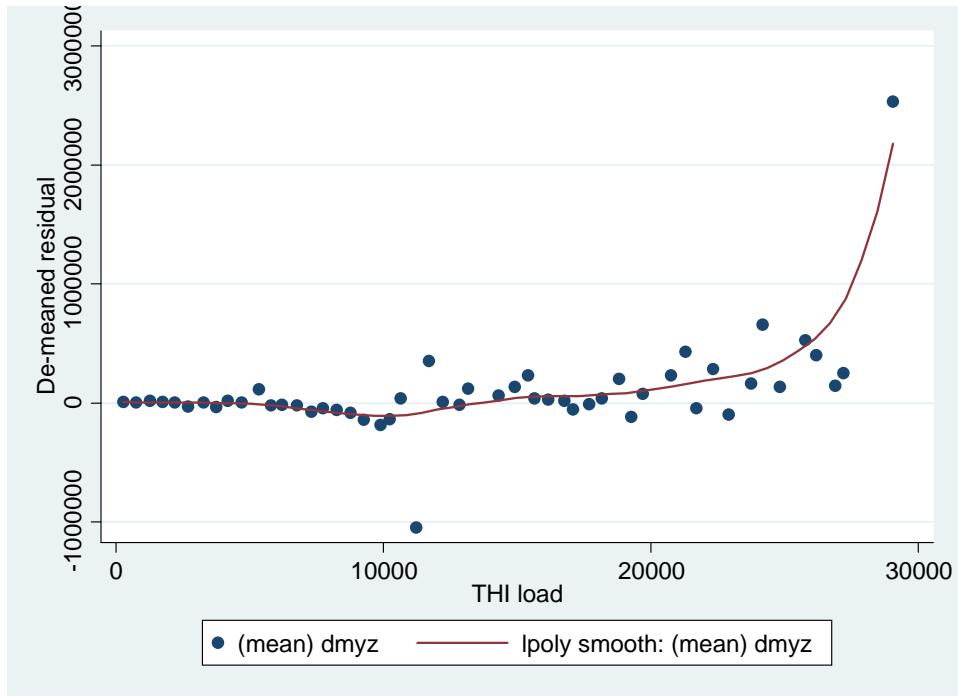
**Fig. 5: Relationship between temperature and THI load**



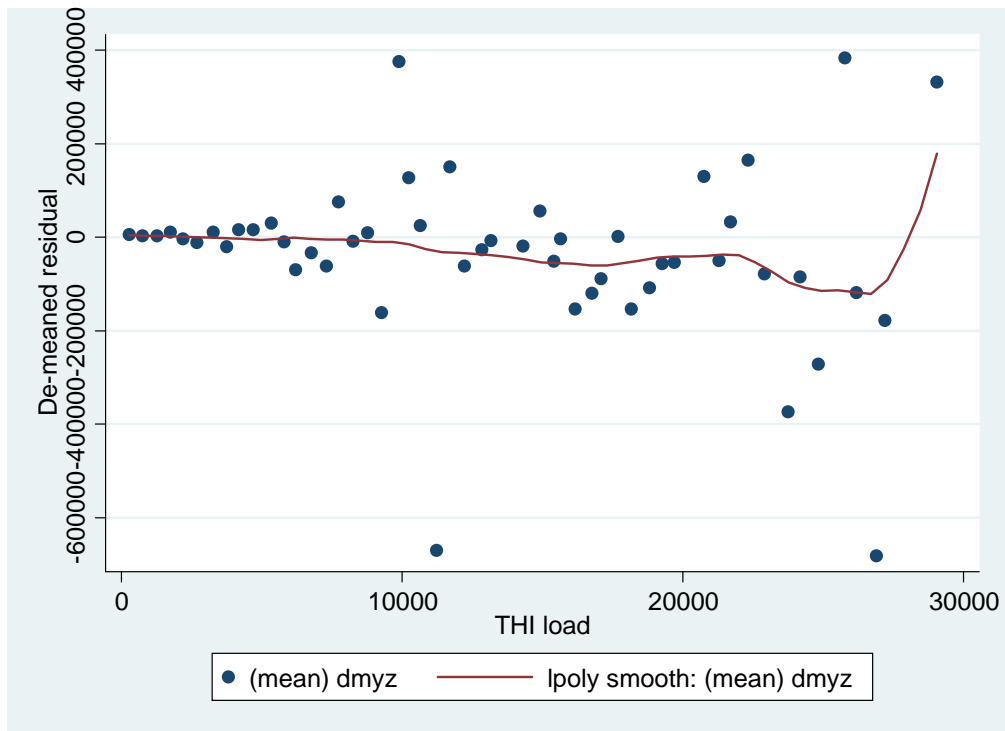
**Fig. 6: Dairy operation size over THI load**



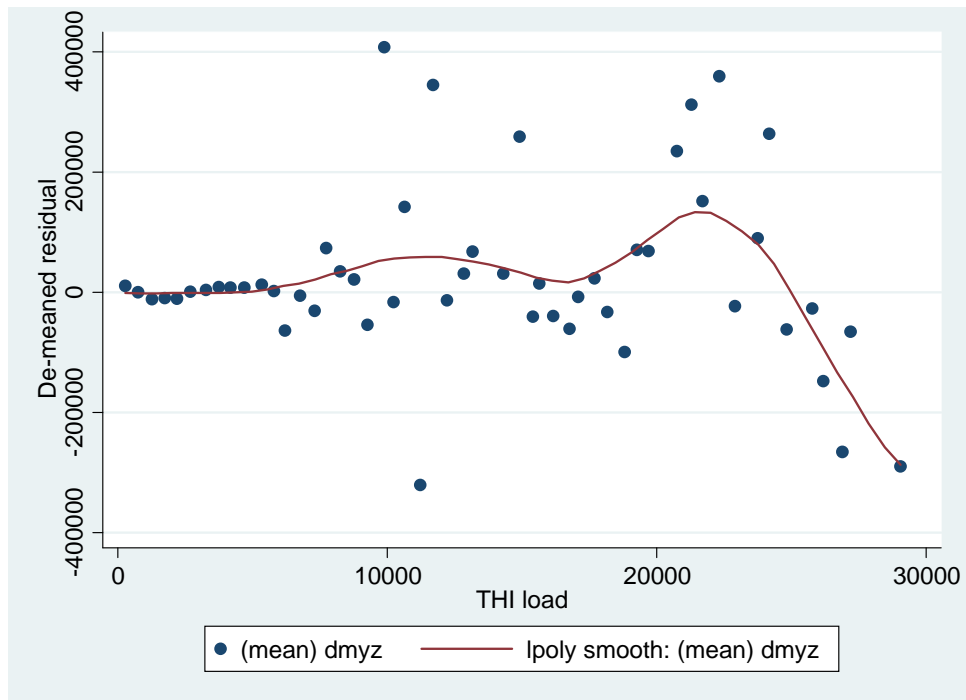
**Fig. 7: Electricity used by THI load**



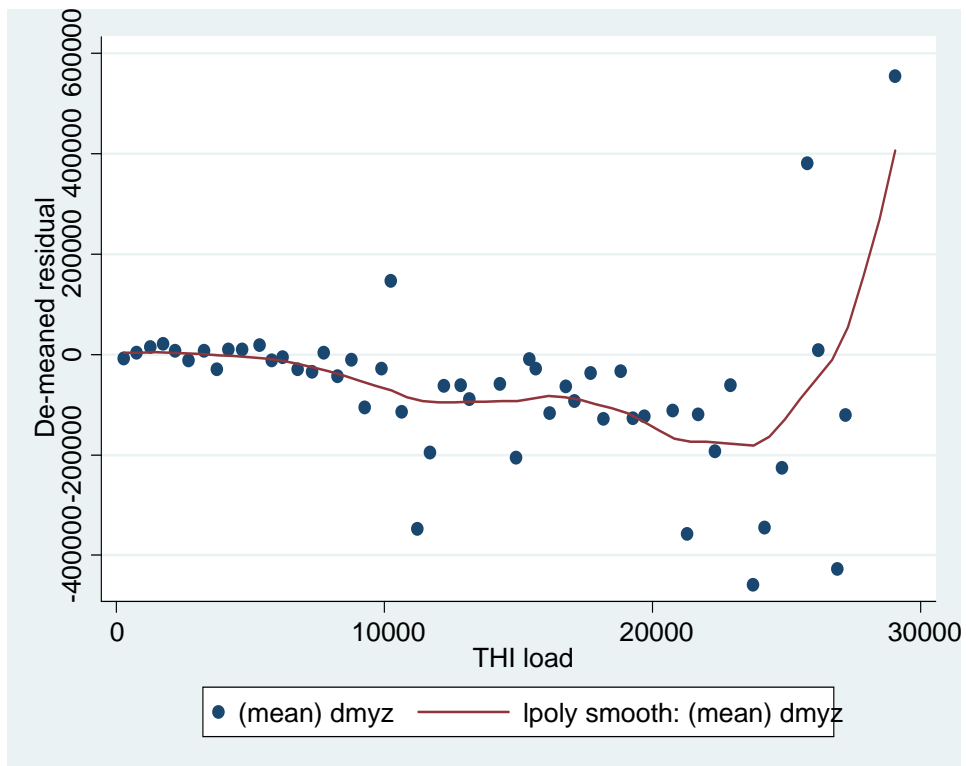
**Fig. 8: Cost of feed by THI load**



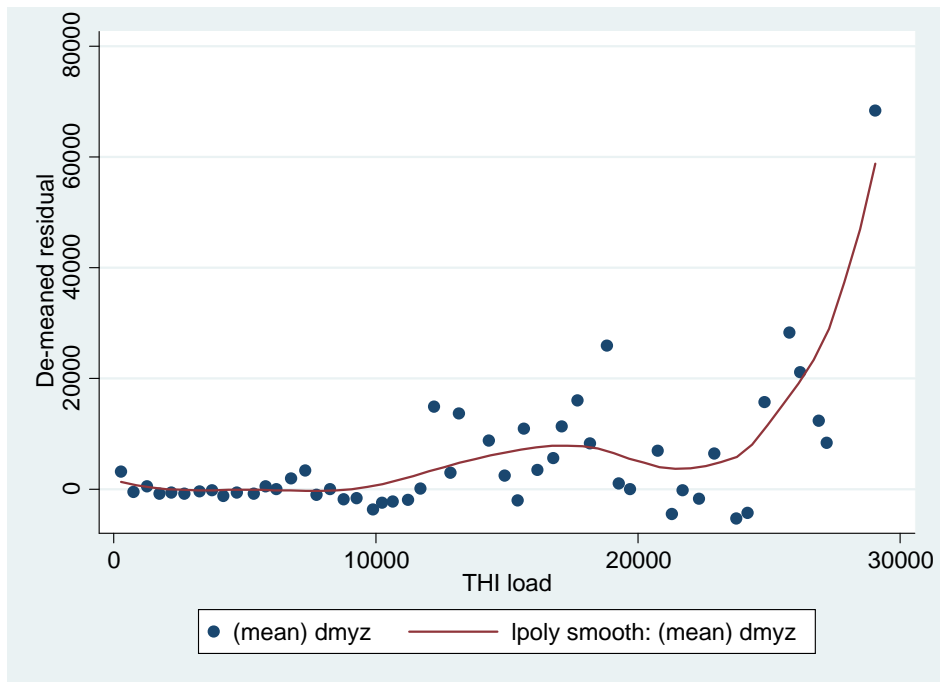
**Fig. 9: Cost of purchased feed by THI load**



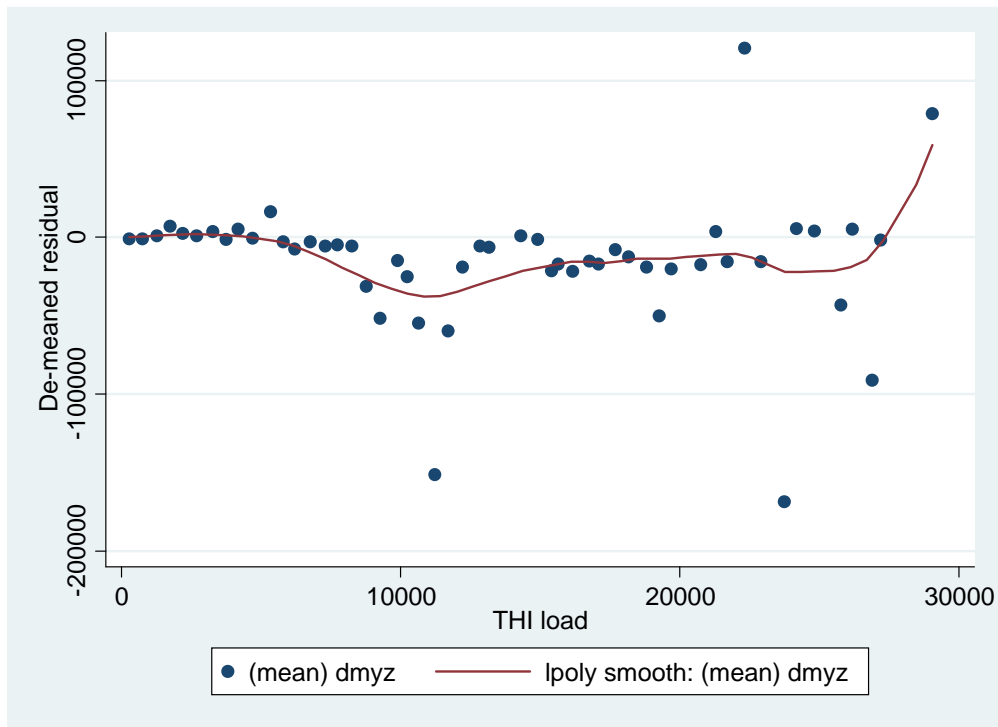
**Fig. 10: Cost of homegrown feed by THI load**



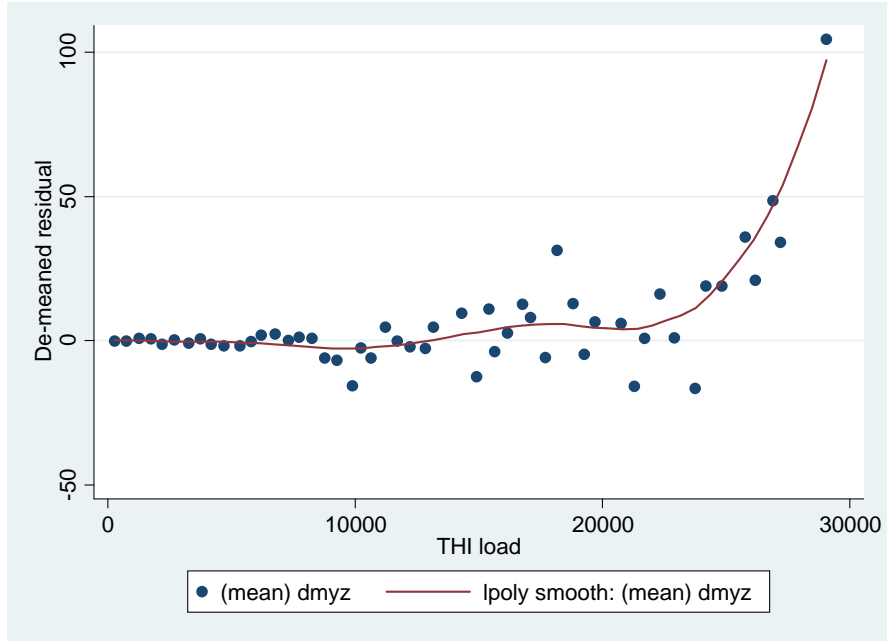
**Fig. 11: Cost of grazed feed by THI load**



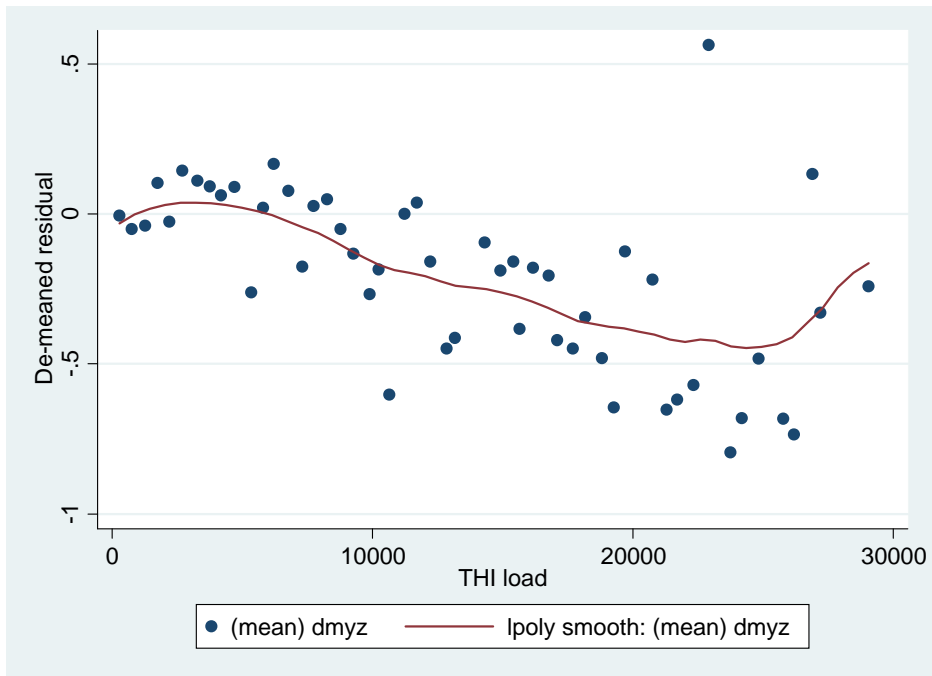
**Fig. 12: Veterinary costs by THI load**



**Fig. 13: Number of head that died by THI load**

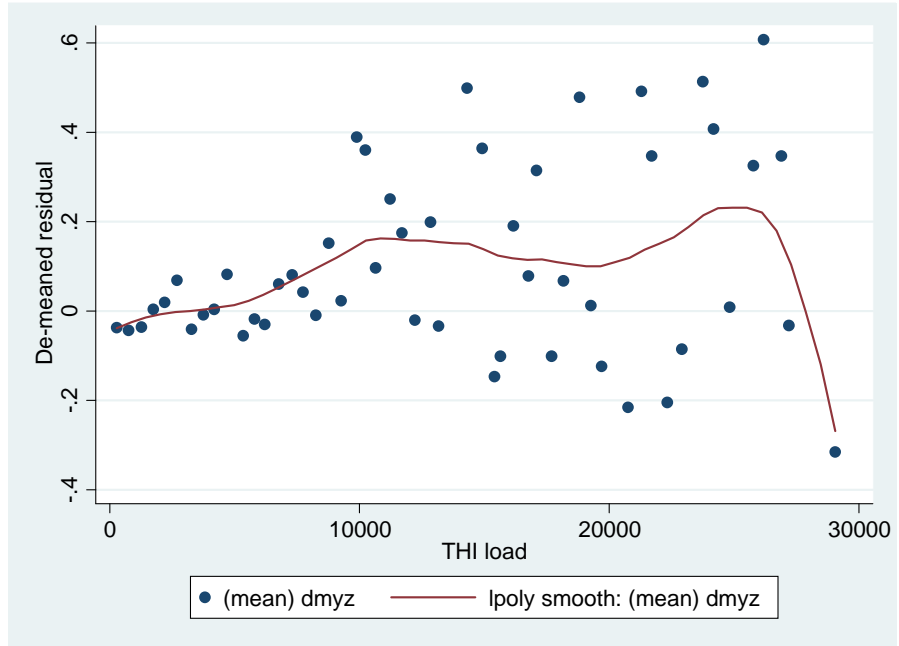


**Fig. 14: Likelihood of freestall barn by THI load**

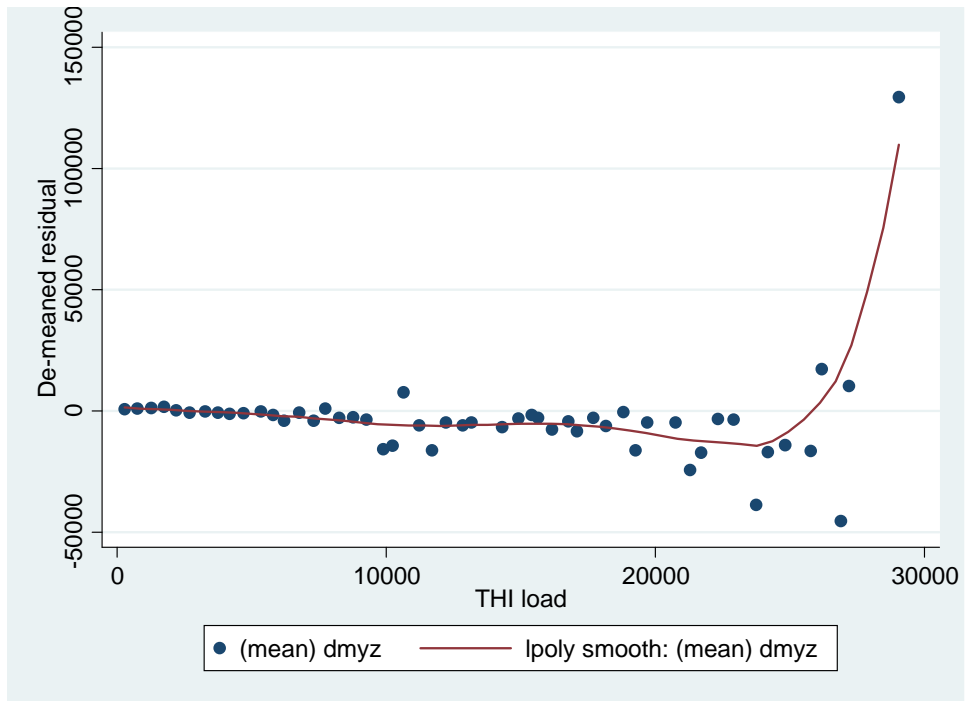




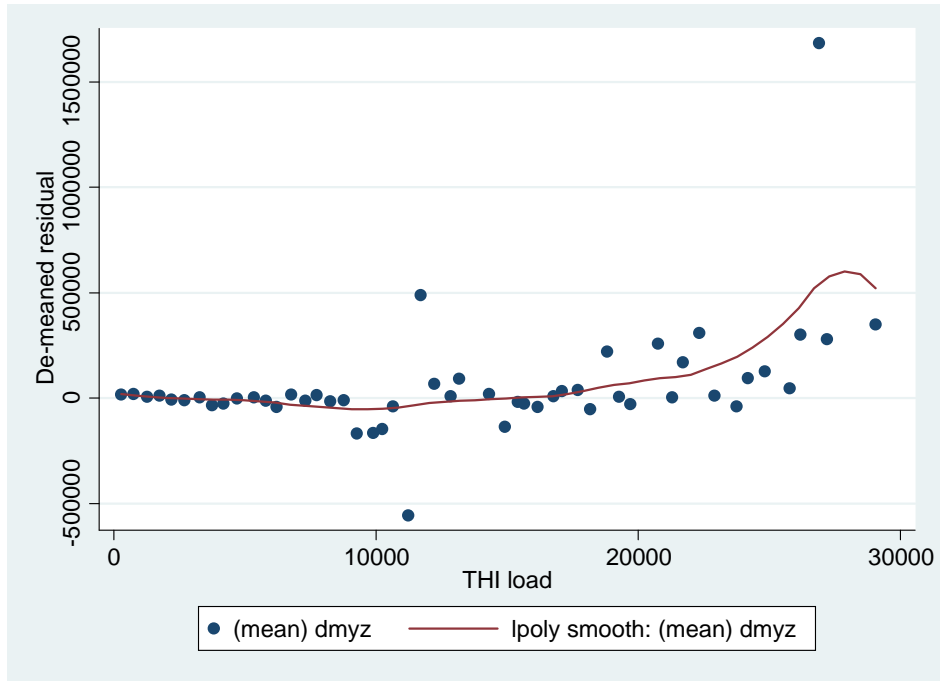
**Fig. 15: Likelihood of dry lot/sun shades by THI load**



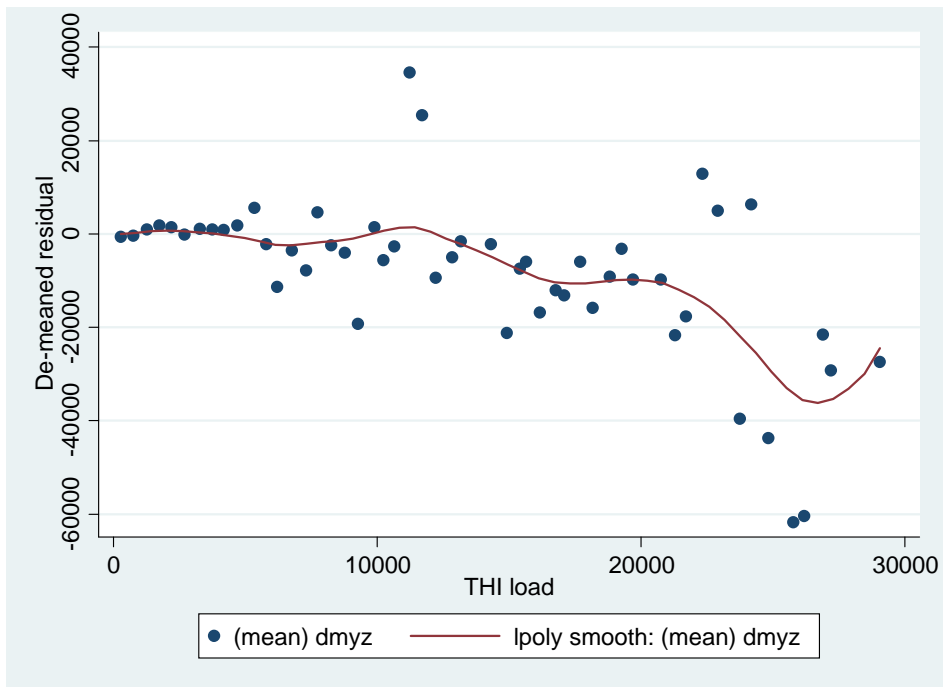
**Fig. 16: Capital costs of housing facilities by THI load**



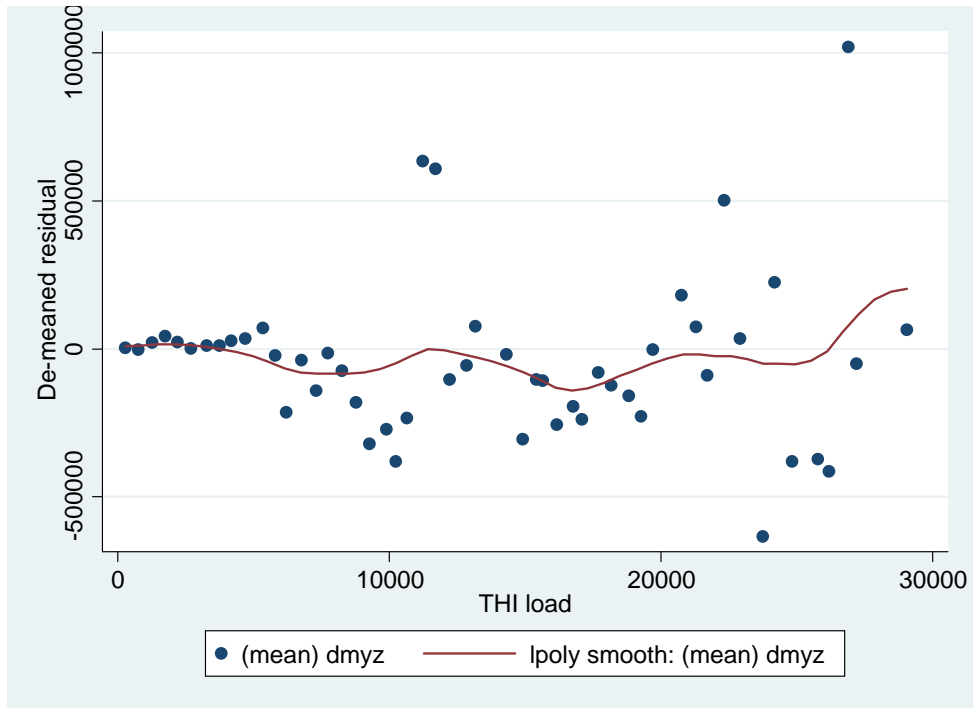
**Fig. 17: Allocated overhead costs by THI load**



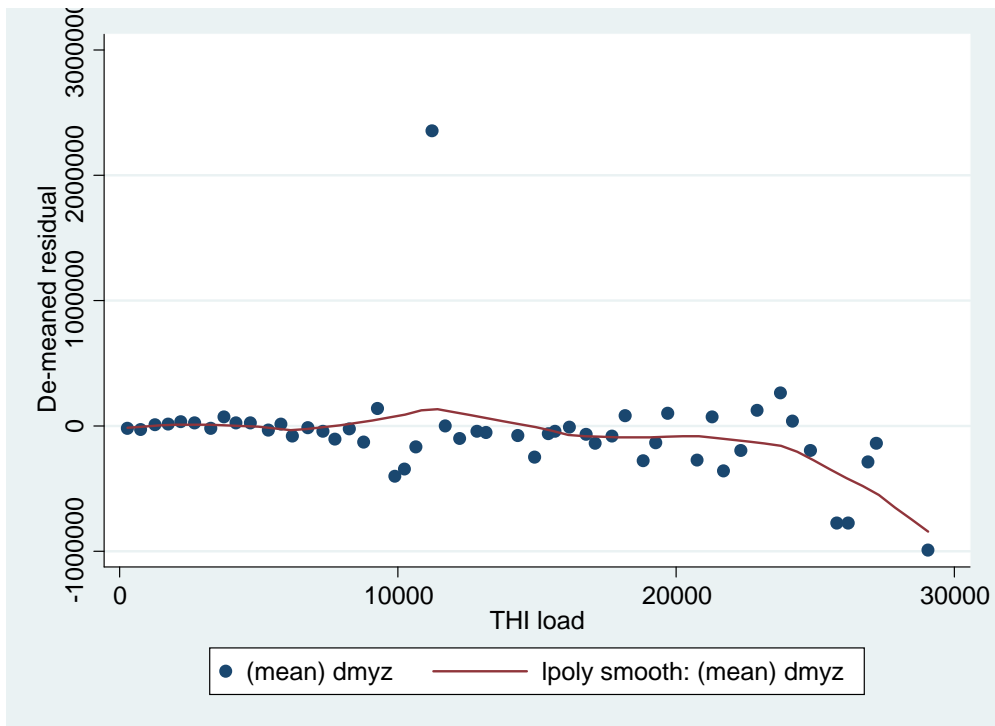
**Fig. 18: CWT of milk produced by THI load**



**Fig. 19: Gross value of production by THI load**



**Fig. 20: Net returns by THI load**



## Appendix: Derivation of Temperature Humidity Index (THI) Load

Allow  $THI_{threshold}$  to be the THI threshold.

$$\text{Let } THI_{mean} = \frac{THI_{max} + THI_{min}}{2} \quad \text{and} \quad Amp = \frac{THI_{max} - THI_{min}}{2}.$$

If  $THI_{max} > THI_{threshold} > THI_{mean}$ , then  $THI_{load}$  is calculated in the following manner:

$$\text{Let } x1 = \arcsin((THI_{threshold} - THI_{mean}) / Amp) \quad \text{and} \quad x2 = \pi - x1.$$

Then

$$THI_{load} = (\cos(x1) - \cos(x2)) \times Amp \times \frac{Period}{\pi} - (x2 - x1) \times \frac{Period}{\pi} * (THI_{threshold} - THI_{mean})$$

If  $THI_{min} < THI_{threshold} < THI_{mean}$ , then  $THI_{load}$  is calculated in the following manner:

$$\text{Let } x1 = \pi \quad \text{and} \quad x2 = \pi + \arcsin((THI_{mean} - THI_{threshold}) / Amp)$$

$$\text{and } p = (\cos(x2) - \cos(x1)) \times Amp \times \frac{Period}{\pi}.$$

Then

$$THI_{load} = Amp \times \frac{Period}{\pi} + (THI_{mean} - THI_{threshold}) \times \frac{Period}{2} + (THI_{mean} - THI_{threshold}) \times \left( (x2 - \pi) \times \frac{Period}{\pi} \right) - p$$

If  $THI_{threshold} < THI_{min}$  then  $THI_{load} = Period \times (THI_{mean} - THI_{threshold})$ .

Finally, if  $THI_{threshold} > THI_{max}$  then  $THI_{load} = 0$ .

**Figure A1. Thermal Humidity Index**

