Journal of Agricultural and Resource Economics 31(3):653–666

Managing Dairy Profit Risk Using Weather Derivatives

Gang Chen, Matthew C. Roberts, and Cameron S. Thraen

Weather conditions are a primary source of dairy production risk. Hot and humid weather induces heat stress, which reduces lactation. Heat abatement, such as ventilation, directly affects the temperature and humidity. Abatement can increase expected profit, but cannot eliminate the lost revenue caused by heat stress. Weather derivatives can reduce weather-induced profit risk and act as a substitute for abatement at the margin. We test the risk management value of weather derivatives in a utility-maximization framework. The result is that weather derivatives can expand the efficient portfolio frontier. Simultaneously using weather derivatives and abatement equipment is more favorable than using either alone.

Key words: abatement technology, mean-variance efficiency, profit risk, weather derivatives

Introduction

Weather conditions are a primary source of dairy production risk. Hot and humid weather induces heat stress, which reduces both the quantity and quality of dairy production (Barth, 1982; Thompson, 1973). Traditional heat abatement technologies control the environment through ventilation, misting, or evaporative cooling (Turner et al., 1992; Lin et al., 1998). Adoption of abatement equipment, however, is hindered by its high initial cost and possibly long payback period. Weather-based derivatives are a relatively new financial product with a positive payout during undesirable weather conditions. These products cannot reduce production risk, but can offset revenue losses. They can be purchased to cover only certain time periods, and may be substitutes for abatement equipment at the margin. The objective of this study is to test the risk management value of weather derivatives in reducing weather-induced profit risk.

The analysis is conducted by constructing two profit models. One is for a representative producer's profit without using weather derivatives or abatement technologies; the other is for the producer's profit using both of these two instruments. Then the producer's optimal portfolio choice is derived in a utility-maximization framework. From the utility framework, the benefit of using weather derivatives for managing risk is measured. The assumptions implicit in this study are: (*a*) the producer has Pratt's absolute risk aversion and chooses mean-variance efficient portfolios with a one-period

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Review coordinated by T. F. Glover.

horizon; (*b*) weather conditions are the only common risk factor to all producers in summer; and (*c*) there are no indivisibilities, taxes, or basis risk.

In each of California, Idaho, Washington, and Wisconsin, one county is identified that produces a significant quantity of milk and for which the National Climatic Data Center has adequate weather records. Using the St-Pierre, Cobanov, and Schnitkey (2003) (henceforth denoted as SCS) biological model of heat stress in dairy cattle, the losses for representative producers are computed for the 36 years for which temperature and humidity data are available. These losses are computed for scenarios in which producers use neither abatement equipment nor derivatives, as well as for the use of each individually and simultaneously. Although abatement is effective at reducing losses from heat stress, our findings reveal the combined use of weather derivatives and abatement equipment can significantly benefit the producer compared to using only physical abatement technologies.

The remainder of the paper proceeds as follows. First, an introduction to weather derivatives and heat stress is provided. Next, we introduce the economic model used to evaluate weather derivatives, followed by a presentation of the empirical results. A brief overview and concluding remarks are given in the final section.

Weather and Weather Derivatives

Weather derivatives are financial contracts in which two parties agree to exchange payments on the basis of observed weather conditions. Common weather derivatives include those on the basis of average temperature, the number of cooling degree days, or the amount of rainfall. Weather derivatives have several unique properties. Because the payoff is calculated based on an observable weather index, there is little moral hazard. Moreover, since weather information is perfectly symmetric, adverse selection is eliminated. Therefore, weather derivatives have an advantage over traditional insurance for hedging against weather-related losses, because there is no need to prove damage to receive payoffs.

Weather derivatives have been the focus of much research. Dischel (1998) argues that due to the non-tradable nature of weather, weather derivatives cannot be valued by the Black and Scholes (1973) option pricing model, and instead a stochastic Monte Carlo simulation with a weather forecast model may be more effective. Examining the weather effects on crop yields, Turvey (2001) suggests weather derivatives might be used as a form of agricultural insurance. Cao and Wei (2001) propose a model for daily temperature, which can incorporate several key properties such as seasonal cycles and uneven variations throughout the year, and develop a pricing model based on Lucas' (1978) equilibrium asset pricing model. Diebold and Campbell (2002) construct a nonstructural time-series model of daily average temperature, which incorporates seasonal changes of temperature levels and variations throughout the year. Most previous research has examined only temperature and/or rainfall derivatives to manage weather risk for energy and field crop markets. To our knowledge, there has been no research on the potential of using weather derivatives to hedge against livestock profit risk.

Economic losses occur in the dairy industry when ambient conditions are outside dairy cows' thermal comfort zone. According to SCS, heat stress in dairy cattle is a function of the temperature-humidity index (THI, also known informally as the "heat index"). Johnson (1987) reports that a THI higher than 72° is likely to have adverse effects on per-cow yield. SCS assert that the lower heat tolerance of the current selection of dairy cows implies the THI threshold for triggering heat stress should be lowered to 70°. Therefore, 70° is used as the threshold for heat stress, $THI_{threshold}$. According to the National Oceanic and Atmospheric Administration (1976), the standard formula for THI is written as: $THI = T - (0.55 - 0.55H)(T - 58)$, where T is temperature in degrees Fahrenheit and H is relative humidity in percent. Since H is expressed as a percentage, it is easy to see that THI is positively correlated with temperature.

THI varies over the course of the day due to changes in temperature and relative humidity. The maximum THI occurs in the afternoon, when the temperature is highest and relative humidity is lowest; and the minimum THI is at night, when the temperature is lowest and relative humidity is highest. In this paper, daily THI refers to daily maximum THI. If the maximum THI is lower than 70° in a day, there is no heat stress for dairy cows.

Dairy Profit Model

Consider a dairy producer who produces without abatement equipment or weather derivatives. His profit is $\tilde{y} = P\tilde{Q} - C$, where P is milk price, $\tilde{Q}$ is the stochastic yield, and C denotes total cost. For analytical simplicity, it is assumed there is no price risk; therefore, price is normalized to unity. Likewise herd size is also normalized to unity. The tilde (˜) denotes a random variable.

Suppose the expected profit of a producer is his historical average, μ, so the difference between $\tilde{y}$ and μ is the producer's profit risk:

$$\tilde{y} = \mu + \theta f(\tilde{x}) + \tilde{\varepsilon}. \tag{1}$$

The profit risk is orthogonally decomposed into two parts. The first part, $f(\tilde{x})$, is the systematic risk arising from weather conditions. The second, $\tilde{\varepsilon}$, is the idiosyncratic risk of the individual farmer's production variability, where $\tilde{\varepsilon}$ is assumed to be uncorrelated with weather conditions. The coefficient θ quantifies the sensitivity of the producer's individual profit to systematic risk. Note that $f(\tilde{x})$ captures systematic risk and increases with $\tilde{x}$. The functional form of $f(\tilde{x})$ is assumed to be linear, i.e., $f(\tilde{x}) = \alpha\tilde{x}$, where $\alpha > 0$. The factors $\tilde{x}$ and $\tilde{z}$ are specified as follows:

$$\tilde{x} = E(\tilde{z}) - \tilde{z}, \tag{2}$$

$$\tilde{z} = \max\left(\widetilde{THI} - THI_{threshold}, 0\right). \tag{3}$$

The factor $\tilde{z}$, which is common to all producers in a region, measures the degree of heat stress, and the factor $\tilde{x}$ is the difference between expected and actual heat stress. If $\tilde{z}$ is less than $E(\tilde{z})$, then heat stress is milder than its expectation, and $\tilde{x}$ is positive. Under the assumptions that

$$E(\tilde{y}) = \mu,\ E(\tilde{\varepsilon}) = 0,\ \mathrm{var}(\tilde{\varepsilon}) = \sigma_{\varepsilon}^2,\ \mathrm{cov}(\tilde{z}, \tilde{\varepsilon}) = 0,\ \mathrm{cov}(\tilde{x}, \tilde{\varepsilon}) = 0,$$

then

$$\theta = \mathrm{cov}\left(\tilde{y}, f(\tilde{x})\right) / \mathrm{var}\left(f(\tilde{x})\right).$$

By substitution, equation (1) becomes:

$$\tilde{y} = \mu + \alpha\theta\tilde{x} + \tilde{\varepsilon} = \mu + \beta\tilde{x} + \tilde{\varepsilon}, \tag{4}$$

where

$$\beta = \operatorname{cov}(\tilde{y}, \tilde{x}) / \operatorname{var}(\tilde{x}). \tag{5}$$

Since the risk to dairy producers is from excessively high $\widetilde{THI}$, call options on THI are the only derivatives considered. The underlying index is $\widetilde{THI}$, and the strike price is $THI_{threshold}$. Without loss of generality, the tick size is set at 1, i.e., one option will bring the holder $1 for each degree of THI above the strike level. Therefore, the value of the payoff from a weather call option, $\tilde{n}$, is equal to $\tilde{z}$.

Because the weather derivatives market is relatively young, and transactions occur almost entirely over-the-counter, transaction costs are imposed on the option premium. The option premium equals the expected payoff plus proportional transaction costs:

$$\pi = (1 + \gamma)E(\tilde{z}), \tag{6}$$

where the loading rate $\gamma > 0$ reflects transaction costs related to administrative and implementation fees and the desirability to the issuers. If γ is zero, the weather options are actuarially fairly priced.

Also suppose that the producer is free to choose his abatement equipment investment η ($\eta \geq 0$, where $\eta = 0$ indicates no abatement equipment). By using abatement equipment, the production loss from heat stress can be reduced. The biological functional form of the effectiveness of abatement equipment is formulated as:

$$\tilde{m} = g(\eta, \widetilde{THI}) = (a + b * \widetilde{THI}) * \sqrt{\eta}, \tag{7}$$

where $\tilde{m}$ is the profit increase resulting from the abatement investment, η is abatement investment,[1] and a and b are parameters.

It is easy to see that $\tilde{m}$ is increasing with η and $\widetilde{THI}$. When $\eta = 0$, $\tilde{m} = 0$, because no benefit can be derived without investment in the abatement equipment. For a given $\eta > 0$, $\tilde{m}$ is increasing with $\widetilde{THI}$. This is merely a reflection of the fact that when $\widetilde{THI}$ is high, abatement equipment is more beneficial (i.e., $\tilde{m}$ is large) even though firm profits may, in fact, be lower. Since the net payoff from using abatement technologies is

$$(a + b * \widetilde{THI}) * \sqrt{\eta} - \eta,$$

the net payoff from investing in abatement equipment is positive if $\widetilde{THI}$ is high enough; otherwise, the net payoff is negative.

With weather options and abatement equipment, the producer's net profit is given by:

$$\tilde{y}^{net} = \tilde{y} + \phi * (\tilde{z} - \pi) + \tilde{m} - \eta, \tag{8}$$

[1] This is a simple one-period, one-agent model. Since abatement equipment is useful for many years once installed, the installation cost is annualized at a certain rate (say 15%) for yearly analysis. Using the "burn-rate" method causes the expected THI to vary little over time. The producer's yearly optimal decision on weather option purchase amount and abatement investment will not change once determined based on current information.

where ϕ is the weather option purchase amount. Therefore, there are two elements the producer is free to choose: quantity of weather options (ϕ), and spending on abatement (η). It is assumed these two choices are determined simultaneously in a portfolio, taking the remaining parameters as given.

The producer's optimal portfolio choice of weather option purchase and abatement investment is derived using a utility-maximization model. The producer is assumed to have a mean-variance utility function[2] of:

$$U = E(\cdot) - \tfrac{1}{2}A * \text{var}(\cdot), \tag{9}$$

where A is an index of an agent's aversion to assuming risk. Then the representative producer's objective is to choose his optimal option purchase (ϕ) and abatement spending (η) to maximize his utility from using weather options and abatement equipment:[3]

$$\max_{\phi,\eta} U^{net} = E(\tilde{y}^{net}) - \tfrac{1}{2}A * \text{var}(\tilde{y}^{net}). \tag{10}$$

Specifically,

$$\begin{aligned} U^{net} &= E(\tilde{y}) + \phi E(\tilde{z} - \pi) + E(\tilde{m} - \eta) - \tfrac{1}{2}A * \big[\text{var}(\tilde{y}) + \phi^2 \text{var}(\tilde{z}) \\ &\quad + \text{var}(\tilde{m}) + 2\phi\,\text{cov}(\tilde{y}, \tilde{n}) + 2\,\text{cov}(\tilde{y}, \tilde{m}) + 2\phi\,\text{cov}(\tilde{n}, \tilde{m})\big] \\ &= \mu - \phi\gamma\mu_{\tilde{z}} + (a + b\mu_{\widetilde{THI}})\sqrt{\eta} - \eta - \tfrac{1}{2}A * \big[\beta^2\sigma_{\tilde{z}}^2 + \sigma_{\tilde{\varepsilon}}^2 + \phi^2\sigma_{\tilde{z}}^2 + b^2\eta\sigma_{\widetilde{THI}}^2 \\ &\quad - 2\beta\phi\,\text{cov}(\tilde{z}, \tilde{z}) - 2\beta b\sqrt{\eta}\,\text{cov}(\widetilde{THI}, \tilde{z}) + 2\phi b\sqrt{\eta}\,\text{cov}(\widetilde{THI}, \tilde{z})\big]. \end{aligned} \tag{11}$$

Take the corresponding first-order conditions with respect to ϕ and η:

$$\gamma\mu_{\tilde{z}} + A\big[\phi\sigma_{\tilde{z}}^2 - \beta\,\text{cov}(\tilde{z}, \tilde{z}) + b\sqrt{\eta}\,\text{cov}(\widetilde{THI}, \tilde{z})\big] = 0, \tag{12}$$

$$\begin{aligned} &\tfrac{1}{2}(a + b\mu_{\widetilde{THI}})\eta^{-1/2} - 1 - \tfrac{1}{2}A\big[b^2\sigma_{\widetilde{THI}}^2 - \beta b\,\text{cov}(\widetilde{THI}, \tilde{z})\eta^{-1/2} \\ &\quad + \phi b\,\text{cov}(\widetilde{THI}, \tilde{z})\eta^{-1/2}\big] = 0. \end{aligned} \tag{13}$$

Then the equation system of (12) and (13) can be solved simultaneously.

It follows from (12) that:

$$\phi^* = -\frac{\gamma\mu_{\tilde{z}}}{A\sigma_{\tilde{z}}^2} + \beta\frac{\text{cov}(\tilde{z}, \tilde{z})}{\sigma_{\tilde{z}}^2} - b\frac{\text{cov}(\widetilde{THI}, \tilde{z})}{\sigma_{\tilde{z}}^2}\sqrt{\eta}. \tag{14}$$

Substituting (14) into (13) and rearranging, gives:

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[2] This framework is equivalent to expected utility function if (net) profit is normally distributed. But either normally distributed profit or a quadratic utility function is sufficient to validate the mean-variance utility model. Meyer (1987) has shown that the mean-variance model is consistent with the expected utility model under much weaker restrictions (see also Pratt, 1964).

[3] Theoretically, if ϕ in the optimal portfolio is negative, this means the decision maker can benefit from selling weather call options.

$$\text{(15)} \qquad \sqrt{\eta^*} = \frac{\left\{ \begin{array}{c} a + b\mu_{\widetilde{THI}} + \gamma\mu_{\tilde{z}} b \dfrac{\text{cov}(\widetilde{THI}, \tilde{z})}{\sigma_{\tilde{z}}^2} \\ + A\beta b \left[\text{cov}(\widetilde{THI}, \tilde{z}) - \dfrac{\text{cov}(\widetilde{THI}, \tilde{z})\text{cov}(\tilde{z}, \tilde{z})}{\sigma_{\tilde{z}}^2} \right] \end{array} \right\}}{2 + Ab^2 \left[\sigma_{\widetilde{THI}}^2 - \dfrac{\text{cov}^2(\widetilde{THI}, \tilde{z})}{\sigma_{\tilde{z}}^2} \right]}.$$

Proposition 1 follows from (14):

- PROPOSITION 1. *The optimal weather option purchase amount is decreasing with abatement equipment investment. Thus it indicates that weather options can act as a substitute for abatement equipment.*

As observed from (15), the denominator is positive, because

$$b^2 \left[\sigma_{\widetilde{THI}}^2 - \frac{\text{cov}^2(\widetilde{THI}, \tilde{z})}{\sigma_{\tilde{z}}^2} \right] = b^2 \sigma_{\widetilde{THI}}^2 \left[1 - \frac{\rho_{\widetilde{THI},\tilde{z}}^2 * \sigma_{\widetilde{THI}}^2 * \sigma_{\tilde{z}}^2}{\sigma_{\widetilde{THI}}^2 * \sigma_{\tilde{z}}^2} \right]$$

$$= b^2 \sigma_{\widetilde{THI}}^2 \left(1 - \rho_{\widetilde{THI},\tilde{z}}^2 \right) > 0,$$

since the correlation coefficient $\rho_{\widetilde{THI},\tilde{z}} \in (0, 1)$.

Also, since $\tilde{m} = (a + b\widetilde{THI}) * \sqrt{\eta}$, this inequality $(a + b\mu_{\widetilde{THI}}) > 0$ implies that abatement investment can reduce loss from heat stress. Then the numerator of (15) is also positive. It therefore follows that:

- PROPOSITION 2. *The optimal abatement investment is positive.*

And proposition 3 also follows from (15):

- PROPOSITION 3. *The optimal abatement investment is negatively related to the producer's risk-aversion degree (i.e., A). That is, the more risk averse the producer, the less he would invest in abatement equipment.*

Substituting (15) back into (14) yields:

$$\text{(16)} \qquad \phi^* = \beta - b \frac{\text{cov}(\widetilde{THI}, \tilde{z})}{\sigma_{\tilde{z}}^2} * \frac{a + b\mu_{\widetilde{THI}}}{2 + Ab^2 \left[\sigma_{\widetilde{THI}}^2 - \dfrac{\text{cov}^2(\widetilde{THI}, \tilde{z})}{\sigma_{\tilde{z}}^2} \right]}$$

$$= \beta - b(a + b\mu_{\widetilde{THI}}) * \frac{\rho_{\widetilde{THI},\tilde{z}} * \sigma_{\widetilde{THI}}}{\left[2 + Ab^2 \sigma_{\widetilde{THI}}^2 (1 - \rho_{\widetilde{THI},\tilde{z}}^2) \right] * \sigma_{\tilde{z}}}.$$

From (16), it follows that:

- PROPOSITION 4. *The optimal option purchase amount is increasing with β. Thus, the more the producer's profit is sensitive to the systematic risk, the more options he should purchase, ceteris paribus.*

It also follows from (16):

- PROPOSITION 5. *The optimal option purchase amount is increasing with the producer's risk-aversion degree, A.*

- PROPOSITION 6. *The optimal option purchase is decreasing with a and b.*

By substituting (16) and (15) back into (11), the maximized increased utility from using weather options and abatement can be derived from:

$$(17) \qquad \Delta U = U^{net}(\phi^*, \eta^*) - U(0,0)$$
$$= (a + b\mu_{\widetilde{THI}}) * \sqrt{\eta} - \eta - \tfrac{1}{2}A\big[\phi^2\sigma_{\tilde{z}}^2 + b^2\eta\sigma_{\widetilde{THI}}^2$$
$$- 2\beta\phi\sigma_{\tilde{z}}^2 - 2\beta b\sqrt{\eta}\,\text{cov}(\widetilde{THI}, \tilde{z}) + 2\phi b\sqrt{\eta}\,\text{cov}(\widetilde{THI}, \tilde{z})\big].$$

It is also possible to compare the cases in which the producer uses only one of these two instruments. The simultaneous usage of weather options and abatement equipment will be more favorable. Therefore, weather derivatives can act as substitutes for traditional abatement technologies.

Data

To empirically evaluate the effectiveness of managing weather risk for dairy producers, equations (4) and (7) must be estimated. Three types of data are needed: weather data, profit data, and abatement investment data. Accordingly, one county from each of California, Idaho, Washington, and Wisconsin was chosen for this analysis on the basis of milk production and availability of temperature and humidity data. For the four counties selected (Kern County in California, Ada County in Idaho, Yakima County in Washington, and Dane County in Wisconsin), 36 years of surface observation were available from the National Climatic Data Center (NCDC).[4] The weather data for each county include daily maximum and minimum temperatures and daily maximum and minimum relative humidities. Daily temperature and dew point[5] both follow seasonal patterns during the year; therefore, the "burn-rate" method works well with these data for pricing weather options. The daily maximum temperature-humidity index (THI) is derived from the daily maximum temperature and minimum relative humidity.

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[4] The 36 years of data are actually not consecutive, but are comprised of two time spans: 1949–1964 and 1984–2003. Between 1965 and 1983, there are no daily relative humidity data available from the NCDC.

[5] Dew point measures how much water vapor is in the air. In many places, the air's total vapor content varies only slightly during an entire day, and so it is the changing air temperature that causes the variation in relative humidity. Related information can be found online at http://www.usatoday.com/weather.

Table 1. Descriptive Statistics of Cumulative Summer Weather Data

State	County	$\mu_{\tilde{z}}$	$\mu_{\widetilde{THI}}$	$\sigma_{\tilde{z}}$	$\sigma_{\widetilde{THI}}$	$\rho_{\widetilde{THI},\tilde{z}}$
CA	Kern	1,271.51	14,086.92	128.31	146.46	0.98
ID	Ada	515.67	12,838.77	83.57	165.27	0.78
WA	Yakima	450.97	12,816.44	99.57	166.55	0.88
WI	Dane	574.64	12,815.72	121.83	181.54	0.83

Definition of terms: $\mu_{\tilde{z}}$ = the summer mean degree days above the heat stress threshold; $\mu_{\widetilde{THI}}$ = the summer mean degree days above 0°F; $\sigma_{\tilde{z}}$ = the standard deviation of summer degree days above the heat stress threshold; and $\sigma_{\widetilde{THI}}$ = the standard deviation of summer degree days above 0°F.

For each county, a representative producer's heat stress losses and the effect on these losses of using abatement equipment are generated from the models in St-Pierre, Cobanov, and Schnitkey (SCS, 2003) (see appendices A and B for details). Because 97% of heat stress occurs between May 1st and October 31st, weather options are assumed to be written only for the summer. The payoff of an option is the cumulative $\tilde{n}$ in the summer, and the premium is the expected payoff. Equations (4) and (7) are estimated using the cumulative summer data. Table 1 reports the descriptive statistics of the cumulative summer weather data.

Estimation and Results

Following SCS, $THI_{threshold}$ is 70°. The daily milk loss during the 36 years and the corresponding daily $\widetilde{THI}$ are calculated using the weather data and the SCS milk loss model. By accumulating the milk loss and $\tilde{z}$ for each of the 36 summers, 36 observations of cumulative losses and $\tilde{x} = E(\tilde{z}) - \tilde{z}$ are available. From a least squares regression, β is estimated. Table 2 gives the estimation results for the four counties. For example, the β of a representative producer in Kern County (CA) is 0.75 kg of milk per cow, which means each degree of $\tilde{z}$ beyond its expectation will induce 0.75 kg milk loss. The milk price is fixed at \$0.287/kg, so the milk loss is \$0.22 per degree of $\tilde{x}$. The sensitivity of milk profits to $\tilde{x}$ varies because of the different climates in the various counties.

The daily weather data are analyzed using the abatement effect model[6] to calculate the daily reduced THI corresponding to seven abatement levels. Multiplying the estimated β and milk price, the increased profit due to abatement investment is calculated. The daily profit effect and THI are accumulated over each summer. Thus for each county, there are 36 observations of cumulative profit changes and THI for each of the six abatement investment levels. Parameters a and b in equation (7) are estimated by least squares regression. Table 3 shows the regression results.

With the estimates of β, a, and b, we can calculate the optimal portfolio choice and investigate the risk management value of weather derivatives and abatement equipment using equations (15), (16), and (17). For the purpose of illustration, the representative

[6] SCS provide three abatement effect models corresponding to three abatement intensity levels. The first model is for only using fans or sprinklers; the second model is for a combination of fans and sprinklers; and the third model is for a specific system, the Korral Cool system, which is used in the Southwest and other dry and hot areas, such as Arizona and Texas. For this paper, six abatement effect functions are linearly simulated using a combination of fans and sprinklers (see appendix B).

Table 2. Least Squares Regression: Beta Coefficient Estimation Results (kg of milk loss)

State	County	β Coefficient (kg)	Std. Error	R^2
CA	Kern	0.75	0.089	0.67
ID	Ada	0.40	0.030	0.83
WA	Yakima	0.30	0.018	0.89
WI	Dane	0.63	0.044	0.86

Note: β is the estimated reduction in milk output in response to a 1 degree day increase above the expected heat stress.

Table 3. Least Squares Regression: Coefficient Estimation of Abatement Effectiveness

State	County	a	Std. Error	b	Std. Error	R^2
CA	Kern	-47.85	11.53	0.0046	0.00082	0.86
ID	Ada	-31.98	2.24	0.0029	0.00017	0.91
WA	Yakima	-38.90	1.43	0.0033	0.00011	0.93
WI	Dane	-50.37	3.88	0.0046	0.00030	0.89

Note: a and b are parameters obtained from the estimation of equation (7), $\tilde{m} = (a + b * \widetilde{THI})\sqrt{\eta}$, where $\tilde{m}$ is increased profit, $\widetilde{THI}$ is the total summer degree days, and η is the abatement investment.

producer's risk-aversion level, which is represented by Pratt's absolute risk aversion (PARA), is set at 0.20.[7]

Because weather derivatives are not currently known to be traded on THI, it is difficult to forecast an appropriate level of transaction costs. Therefore, the level of transaction costs (γ) is set at 5%.

To compare the risk management effectiveness of the instruments, three scenarios are investigated:

1. Only use abatement equipment.
2. Only use weather options.
3. Use both abatement equipment and weather options.

The results are reported in table 4. Using a producer in Kern County as an example, the optimal use of abatement equipment (scenario 1) results in a $94 net increase in certainty equivalent utility. The use of only weather options (scenario 2) is less effective, resulting in a $61.86 increase in certainty equivalent utility. However, in scenario 3, when a producer is free to use both abatement equipment and options, the producer's utility increases by a certainty equivalent amount of $131.23.

According to our findings, without using the instruments, the mean and variance of the Kern County producer's summer revenue loss due to heat stress are $161.46 and $1,132.28, respectively. Thus, by the mean-variance model, the utility loss of a farmer

[7] See, for example, Pratt (1964). Note that in this paper, we make no assumption about whether the risk aversion parameter is constant, decreasing, or increasing with initial wealth levels. We are studying a representative farmer who faces an opportunity to buy weather options which will not change his expected wealth level, and needs to decide how much money to invest on weather options. Therefore, we have an implicit assumption that changes of expectation and variance of profit due to using abatement equipment and weather options will not affect his risk-aversion degree.

Table 4. Risk Management Effectiveness by Scenario ($)

		Scenario 1		Scenario 2			Scenario 3			
State	County	η^*	ΔU	$\phi^*\pi$	ψ^*	ΔU	$\phi^*\pi$	ψ^*	η^*	ΔU
CA	Kern	90.10	94.00	260.40	72	61.86	159.11	73	69.52	131.23
ID	Ada	9.21	9.42	42.54	72	6.23	32.71	73	7.92	14.49
WA	Yakima	5.33	5.49	39.38	72	5.72	22.41	73	4.12	9.88
WI	Dane	31.02	33.15	81.58	72	42.36	69.85	72	20.06	62.92

Notes: ΔU is the certainty equivalent (in $) of the increase in utility from using the instrument(s) available in the scenario compared to the baseline scenario (no abatement, no weather derivatives); η^* is the optimal abatement investment; ϕ^* is the optimal weather derivative purchase; and ψ^* is the optimal strike price for the weather derivatives. Scenario 1 uses only abatement equipment, scenario 2 uses only weather options, and scenario 3 allows both abatement equipment and weather options.

with PARA of 0.20 is −$274.68 in certainty equivalent. Therefore, in scenario 3, the optimal use of these two instruments can reduce losses due to heat stress by $131.23/ $274.68 = 48%. The utility loss can be reduced by 34% and 23% in scenarios 1 and 2, respectively.[8]

Figure 1 displays the increase in certainty equivalent profit over the base scenario (no abatement/no weather derivatives) at varying levels of risk aversion for each of the four counties. Clearly, using an optimal combination of abatement and weather derivatives is preferred to the optimal level of either abatement or options at all but the smallest levels of risk aversion. If a producer is risk neutral, i.e., his PARA is zero, using weather options will bring him no benefit because they cannot affect the expected return of the dairy operation. Therefore, for risk-neutral producers, there is no benefit beyond the use of abatement.

As observed from figure 1, location also influences the relative value of weather derivatives. Of the four locations, Kern County, California, benefits the most from the availability of weather derivatives—producers there would be willing to pay up to $46.25 to have weather derivatives available in addition to abatement equipment. Dane County, Wisconsin, producers would be only $33.14 better off, whereas residents of Ada County, Idaho, and Yakima County, Washington, would be less than $10 better off. The differences in benefits to the counties are influenced by the level and variability of temperature and relative humidity in the four locations. As shown in table 1, Kern County has the highest number of THI degree days and variability in degree days, and for this reason, the use of weather derivatives is most effective.

Cross-Validation Analysis

The robustness of these results can be investigated through cross-validation. Specifically, every 35-year subset of the 36 years of data is used to estimate the β in equation (4) and a and b in equation (7). From the parameter estimates, we derive the optimal portfolio choice, i.e., ϕ^* and η^*. By applying the optimal portfolio to the remaining year, the out-of-sample performance of weather options and abatement equipment can be evaluated and compared.

[8] To investigate the impact of transaction costs, table 4 was also generated for the case of no transaction costs ($\gamma = 0$) and $\gamma = 0.20$. For $\gamma = 0.20$, the CE of profit for using abatement and weather derivatives for Kern, Ada, Yakima, and Dane counties is $114.82, $11.98, $7.98, and $55.60, respectively. Full results are available from the authors upon request.

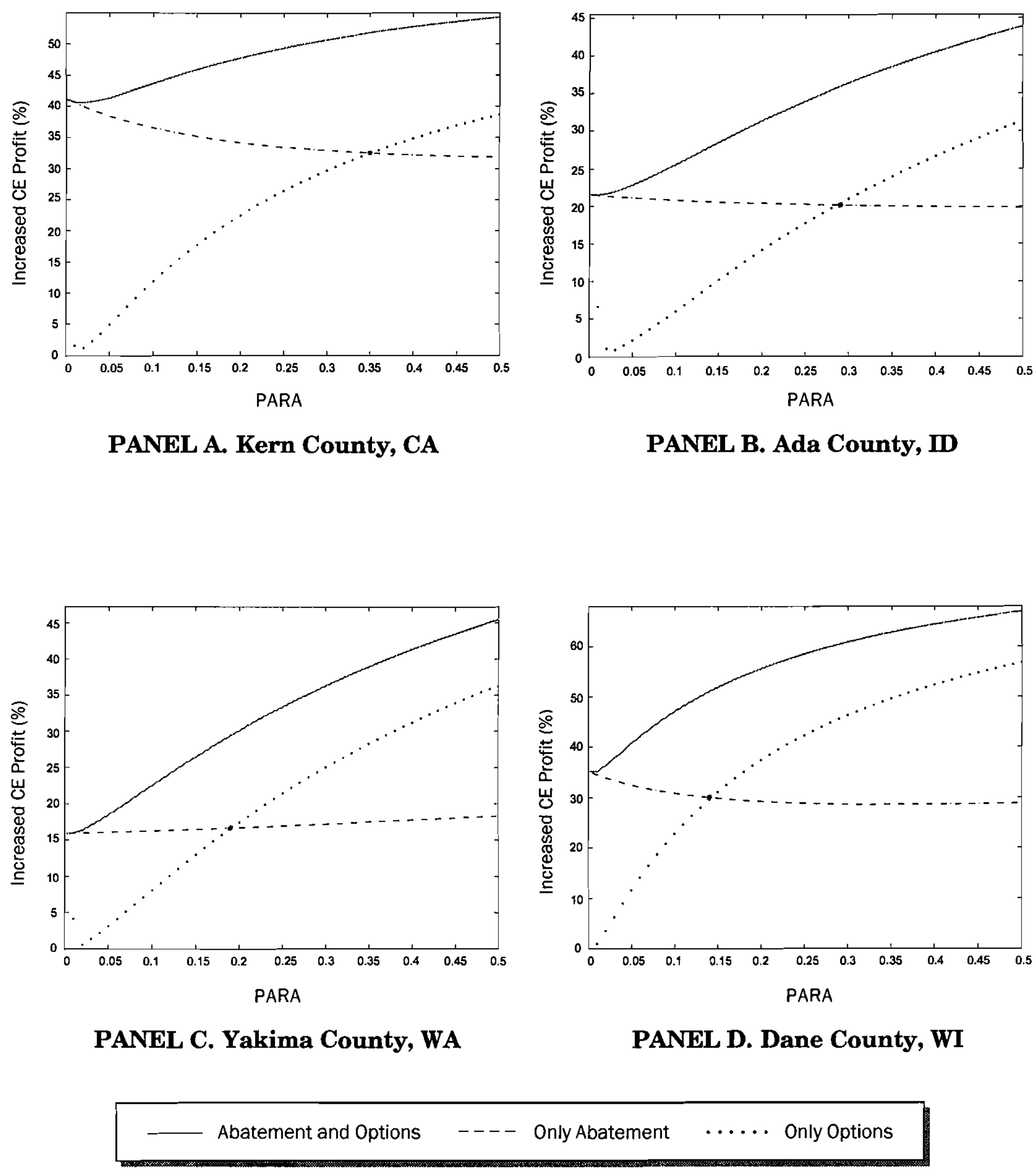

Figure 1. Increased utility with different Pratt's absolute risk aversion values (PARAs)

Table 5. Cross-Validation Results

		Loss Without Instruments ($)				*Loss With Instruments* ($)				
State	County	Mean	Std. Dev.	Min.	Max	Mean	Std. Dev.	Min.	Max.	*Positive*
CA	Kern	161.46	33.65	99.50	259.79	95.22	20.48	64.77	151.33	36
ID	Ada	35.13	10.53	14.22	64.60	27.60	5.02	20.02	44.09	28
WA	Yakima	24.24	9.23	6.17	49.90	20.43	3.60	14.43	28.07	24
WI	Dane	56.78	23.73	18.52	120.94	36.95	10.68	19.22	62.11	29

Notes: *Loss Without Instruments* is the summer profit loss due to heat stress without using abatement equipment or weather options; *Loss With Instruments* is the summer net profit loss due to heat stress with using the two instruments; and *Positive* is the number of positive net payoffs from using the two instruments in the 36 out-of-sample tests.

Results show that the estimates of β, a, and b are quite robust.[9] For instance, the mean of the 36 estimates of β in Kern County is 0.75 kg/cow, and the standard deviation of these estimates is 0.0898 (table 2). The optimal portfolio choices are robust as well, as shown by the results reported in table 5. Both the means and the standard deviations of the 36 out-of-sample profit reductions in the four counties are significantly decreased when using weather derivatives and abatement equipment. For example, the mean of the 36 out-of-sample observations in Kern County is -$161.46 per cow, and the standard deviation is $33.65; when using the two instruments, the respective mean and standard deviation values are -$95.22 and $20.48.

According to the cross-validation analysis, the optimal portfolio is preferable to the abatement-only portfolio in most years. Moreover, the two-instrument portfolio is only less profitable when weather conditions favor milk production, i.e., the milk losses are relatively low. Therefore, using weather options together with abatement equipment can smooth the producer's yearly net revenue—a desirable result for risk-averse producers.

Conclusion

To our knowledge, this study is the first to investigate the potential of weather derivatives in hedging against dairy profit risk arising from heat stress. A representative dairy producer's profit risk is decomposed into systematic risk from weather conditions and idiosyncratic risk which is uncorrelated with weather conditions. With access to hypothetical weather derivatives and abatement equipment, the producer's optimal portfolio choice of these two instruments is derived in a mean-variance utility-maximization framework. The results suggest that weather derivatives can act as a substitute for abatement technologies. Further, the simultaneous usage of these instruments is more favorable than using either of them alone.

This paper provides a link of the burgeoning weather derivatives literature in agricultural economics to a real-world application in which an easily quantifiable weather metric (daily THI in excess of a biological threshold) is the primary source of production risk for a major agricultural commodity. Moreover, unlike other possible applications of weather derivatives, dairy is unique in that weather derivatives are likely substitutable for capital investment in heat abatement equipment, such as fans or water misters.

[9] In the interest of brevity, the detailed results of parameter estimates are not reported.

This research also raises many questions of relevance to the economic community, such as the optimal contract design, basis risk from location difference between weather derivatives and actual production area, whether the existence of these contracts reinforces economies of scale in dairy production, what level of sophistication is required to effectively utilize these tools, and finally, what size of a dairy is required to use weather derivatives. These questions may be of interest for further research.

[*Received May 2005; final revision received July 2006.*]

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Appendix A: Milk Loss Function

The milk loss model in St.-Pierre, Cabanov, and Schnitkey (SCS, 2003) is written as:

$$MILK_{loss} = 0.0695 \times (THI_{max} - THI_{threshold})^2 \times Duration,$$

where $MILK_{loss}$ is in kilograms, and *Duration* is the proportion of a day in which heat stress occurs (i.e., $THI_{max} > THI_{threshold}$) for dairy cows maintained in a system of minimal cooling.

With the assumption that daily THI follows a perfect sine function with a period of 24 hours,[10] the process for calculating the *Duration* of heat stress is detailed as follows:

$$THI_{mean} = (THI_{max} + THI_{min})/2$$

$$\texttt{if } THI_{max} < THI_{threshold}$$

$$Duration = 0$$

$$\texttt{elseif } THI_{min} \geq THI_{threshold}$$

$$Duration = 24$$

$$\texttt{elseif } THI_{mean} > THI_{threshold}$$

$$Duration = \left(\pi - 2 \times \arcsin\left(\frac{THI_{threshold} - THI_{mean}}{THI_{max} - THI_{mean}}\right)\right) \Big/ \pi \times 12$$

$$\texttt{else } Duration = \left(\pi + 2 \times \arcsin\left(\frac{THI_{mean} - THI_{threshold}}{THI_{max} - THI_{mean}}\right)\right) \Big/ \pi \times 12$$

$$\texttt{end}$$

Appendix B: Abatement Effect Function

In SCS, for a 50 m^2 cow pen, which can hold 7.1759 dairy cows, when the annualized fixed costs are \$310, the corresponding operating costs are \$0.0685/hour of operation. The abatement effect is:

$$\Delta THI = -17.6 + (0.36 \times T) + (0.04 \times H),$$

where ΔTHI is the change in apparent THI, T is ambient temperature (°C), and H is ambient relative humidity in percent.

Based on the above specifications, we linearly simulate six abatement effect functions corresponding to six fixed cost levels. These six fixed cost levels are \$130, \$190, \$250, \$370, \$430, and \$490, respectively. That is, all the parameters in a simulated model are proportional to those in the SCS model, with the proportion equal to the ratio of fixed cost levels.

Finally, we define the producer's reduced loss by:

$$\tilde{m} = \max\left(\min(THI_{max} - THI_{threshold}, \Delta THI), 0\right) \times \beta \times MILKPRICE.$$

[10] This assumption accounts for the extent and cumulative severity of heat stress over the course of a day. SCS state that this assumption underestimates the duration of heat stress at higher latitudes in summer, but the gains in accuracy from using more complex models are small.