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Weather Derivatives for Specific Event Risks in Agriculture

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This paper examines the economics and pricing of weather derivatives in Ontario and argues that weather derivatives and weather insurance can be used as a form of agricultural insurance. Using historical data, the relationship between crop productivity and weather is examined. Then a variety of put and call options for rain- and heat-based weather risk are discussed and numerically evaluated. The evaluation examines in detail the pricing of insurance contracts at a given location and across space.

The role of weather in agriculture and other industries is creating an emerging market for weather-based insurance and derivative products. In the United States, companies such as WorldWide Weather Insurance Inc., American Agrisurance Inc., and Natsource (a New York City brokerage) all offer weather-risk products, and in Canada, Royal Bank Dominion Securities Inc. is now brokering weather-specific derivative products. In the fall of 1999, the Chicago Mercantile Exchange listed futures contracts on heating and cooling degree-days for a number of U.S. cities. Applications are widespread among natural gas, oil, and electricity sectors, but more and more such products are being used for agricultural insurance purposes. For example Agricorp, the crown corporation charged with providing crop insurance to Ontario farmers, initiated in the spring of 2000 a pilot project aimed at replacing its biophysical simulation model for forage insurance with a rainfall insurance plan. Agricorp's literature describes the plan as follows:

> Forage 2000 simply offers protection against drought. It is based on the simple concept that rainfall influences production and within reasonable limits, increased moisture levels during the growing season should positively impact forage production. Under the proposed plan, insured customers will receive a claim payment if the measured rainfall over a specified period (May–Aug.) is less than the long-term average. The benefits of the pilot project are: it is simple to understand, as only one peril is insured; it is predictable, as the customer can follow

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> the rainfall accumulation throughout the growing season and determine if they will receive a claim or not. It will also be timely. Claim payments can be made in September when the final rainfall values are collected.
>
> Growers will be able to customize their insurance coverage to suit their farm's needs. They can choose a rainfall collection site, located within townships approximately every 15 km in the pilot area that best fits the weather patterns on their farm. Each site will be underwritten according to its long-term average. Customers will also be able to determine the dollar value of their forage crop, and premiums will be calculated as a percentage of this dollar value . . .
>
> Rainfall is collected at predetermined sites using AGRICORP's own rainfall gauges. These gauges collect all traces of rainfall and log it in 0.2 mm increments for an accurate and equitable determination of the total amount.
>
> Customers have the option of choosing the site that best represents the rainfall on their farm. In order to choose wisely, customers will be provided with station location and underwritten values based on long-term precipitation records.

Weather derivatives can provide a hedge against production rather than price risk in agriculture. Conditions that are too cool or too hot, too dry or too wet affect production of crops in a variety of ways. Most perils commonly insured in crop production can be linked to specific weather events. Rainfall and heat extremes affect evapotranspiration and phenologic growth directly, but certain conditions will also give rise to pestilent and viral infestations.

The weather derivative can be brokered as an insurance contract or as an over-the-counter (OTC) traded option. It is described by specific language which identifies three main criteria: (1) the insured event, (2) the duration of the contract, and (3) the location at which the event is measured. The types of contracts used to insure weather events are varied, but in general there are two different types. First are straightforward derivative products based upon such notions as cooling degree days above 65°F (an indication of electricity demand for air conditioning), heating degree days below 65°F (an indication of electricity, oil, and gas demand required for heating), and growing degree days or crop heat units measured by average daily temperatures above 50°F. These products are similar to conventional put and call options.[1] Second are single- or multiple-event contracts that provide a fixed payout when the specific event occurs. An agribusiness firm may want to insure against multiple events of daily high temperature exceeding 90°F for 7 days straight in order to compensate for yield and/or quality loss or a crop insurer may want to insure against drought events such as no rain for 14 days straight during critical stages in crop development. Such contracts may allow for multiple events and will usually provide a fixed payoff per event.

The purpose of this paper is to explore the economics and pricing of weather-related insurance products for agriculture. The advantage of considering these products over conventional individual yield crop insurance, area-yield crop insurance, or crop insurer reinsurance is that the payoff is contingent on a specific event occurring. The specific event, heat based or rainfall based, is correlated with yield shortfalls, but unlike conventional insurance, the payoff structure is independent of actual crop yields or crop yield indemnities. This removes the role of the adjuster in calculating yield claims while eliminating any possibility of moral hazard. Adverse selection is minimized or eliminated because premiums based on specific events such as rainfall are uncorrelated with the participation rates of producers in the program.

This paper accomplishes several goals. First, I place production uncertainty in the context of specific-event risks and argue that insuring the event that causes damage can be just as effective as insuring the damage itself. Second, I estimate the relationship between heat in growing degree days and rainfall on (Oxford County, Ontario) detrended county corn, soybean, and hay yields and find that up to 30% of county yield variability can be attributed to heat and rainfall events from June 1 to August 31. Third, I explain the structure of both heat and rainfall derivatives as they relate to crop yield risks, premiums, and payoffs. A variety of heat and rainfall derivative products are examined at a specific location (Woodstock, Ontario). I then present a comparative analysis of rainfall derivatives at three different locations at Woodstock, Ottawa, and Welland, Ontario. The products presented in this paper represent actual products offered by insurance companies and brokerages. However, the products have not been widely used in agriculture and in this respect this paper offers a different and new perspective on risk management in agriculture. Given the interest in examining new forms of agricultural insurance such as that described in Skees and Barnett, the material presented in this paper should have significant appeal to practitioners and academics alike.

Weather Insurance and Area-Yield Insurance, in Agricultural Economies

Although weather insurance has only recently become popular, there have been a number of academic investigations dealing with the issue of rainfall insurance in agriculture (there are no known studies on heat insurance in agriculture). Bardsley, Abey, and Davenport investigated the feasibility of rainfall insurance in the dryland wheat growing area of Australia. The conclusions of this study suggested that rainfall did not contribute enough specific risk to income variability to justify even the administrative costs of publicly provided rainfall insurance. These conclusions were later questioned by Quiggen. In developing countries, Patrick was able to show that there would be a demand for rainfall insurance in Mali and in papers by Sukarai and Reardon for Burkino Faso, and Gautman, Hazell, and Alderman for Tamil Nadu in South India, the latent demand for rainfall or drought insurance would be enough to cover the cost of risk plus administrative costs. Sukarai and Reardon found that the demand for rainfall insurance is correlated with drought zones and how households manage ex ante and ex post risks. For example, relative wealth matters, since wealthier households are better positioned to withstand drought and the availability of food aid, which would reduce the downside risk of malnutrition, would decrease the demand for rainfall insurance. Gautman et al. found similar results and suggested a host of resolutions to drought mitigation including increased buffer savings or improved financial markets with savings and lending. The covariate risk spread over large areas may be problematic in terms of risk pooling, but Gautman et al. describe a rainfall lottery in which indemnities are paid if rainfall in a given area falls short of a trigger. The payoff structure to such a lottery is very similar to the payoff structure of the insurance products discussed in this report.

The nature of weather insurance is such that there may be covariate or systematic effects over a particular area. The problem of covariate risks is addressed in the U.S. GRP area-yield crop insurance plan for forages and other crops. The ideal area-yield policy would be one that is free of moral hazard and adverse selection

(Miranda), but in reality adverse selection is problematic because of the nature of risk pooling, and the benefits to area-yield crop insurance in terms of risk reduction are not as high as for individual crop insurance (Turvey and Islam). Certain remedies to increase the efficacy of area-yield crop insurance have been proposed such as adding flexibility and choice at the farm level (Smith, Chouinard, and Baquet; Mahul). In contrast, weather insurance is free of moral hazard and adverse selection because the insured outcome is based on transparent, easily observed criteria (e.g., rainfall at a specific site) versus hidden criteria such as the average yield. Like area-yield insurance, there could be substantial basis risk between the point of measurement and the point of risk. However, either triangulating weather data to a specific point or providing insureds with the flexibility to choose and combine weather stations can remedy this to some extent.

Defining Specific Event Risk

Specific event risk refers to those specific events for which the outcome is known with certainty. The statement "if there is a drought, there will be a crop failure" is a simple example of this concept. The specific event "drought" will, with 100% certainty result in a "crop failure." Consequently, insurance conditioned on specific event risks draws a parallel with cause and effect. The significant departure from traditional crop insurance is that the cause (or event) is insured, not the effect. Put another way, a weather derivative on a specific event (the cause) would be purchased (or sold) to hedge production risks (the effect). Significantly, this implies that crop-yield damage does not have to be proven in order to receive a benefit from an insured specific event.

Specific event risks in agriculture would be defined in terms of production risks tied to specific weather conditions at different stages of phenologic such as sowing to germination, seedling emergence, tassel initiation to silking, or grain filling (Kaufmann and Snell). Examples of specific event risk include two-week drought prior to the tasseling stage in corn growth; excessive preharvest heat that causes diminished oil production from soybeans; frost prior to a specific date; hail at any point prior to harvest; or excessive rains after crop maturation that inhibits or prohibits harvest.

Weather Events and the Economics of Production

In this section, I develop a simple model of agricultural production that captures the marginal response of crop yields to weather events. Using a Cobb–Douglas production function, the model is then applied to actual yields and weather conditions at Woodstock, Ontario.

The model requires a slight departure from classical production economics that measures output as a function of inputs such as fertilizer, chemicals, and labor. Exogenous factors such as weather are traditionally assumed to be constant or relegated to white noise. The current model evaluates yields based on the relationship between exogenous weather factors holding inputs constant. Consequently, the marginal effects of heat and rainfall on crop yields and the marginal productivity of weather can be measured.

In this paper a production function of the Cobb–Douglas type is assumed[2]

$$Y = AR^{\beta 1}H^{\beta 2}, \tag{1}$$

where Y represents crop yields, A is an intercept multiplier, R is cumulative daily rainfall, H is cumulative crop heat units above 50°F, and β are the production coefficients or elasticities of heat and rainfall. Using equation (1), the marginal productivities of rainfall and heat are given by

$$\partial Y/\partial R = \beta_1 Y/R, \tag{2}$$

$$\partial Y/\partial H = \beta_2 Y/H, \tag{3}$$

and

$$\partial^2 Y/\partial R \partial H = \beta_1 \beta_2 Y/R. \tag{4}$$

The necessary conditions for weather insurance to be effective are that $\partial Y/\partial R > 0$, $\partial Y/\partial H > 0$, and $\partial^2 Y/\partial R\partial H \geq 0$. If $\partial^2 Y/\partial R\partial H > 0$, then both rain and heat jointly impact yields. If $\partial^2 Y/\partial R\partial H = 0$, then either rain or heat or both have no effect on yields. The hypothesis to be tested is that $\beta_1 = \beta_2 = 0$. Failure to reject the null hypotheses would indicate that weather does not impact crop yields and thus weather insurance products would be ineffective. If either one or both of the hypotheses is rejected, then specific-event weather insurance could be effective. Effectiveness can be measured by the weather elasticity or the value of β, which measures the percentage change in the crop's yield given a percentage change in weather.

Estimating Weather Effects on Crop Yields

In this section, the effects of cumulative rainfall and cumulative degree-days above 50°F on corn, soybean, and hay yields in Oxford County, Ontario are estimated. Data on county yields were collected from 1935 to 1996 using statistical reports from the Ontario Ministry of Agriculture Food and Rural Affairs (OMAFRA). Daily rainfall and average daily temperatures were obtained from the Environment Canada weather station at Woodstock, Ontario, which is somewhat central to the county. Three years (1942, 1948, and 1972) are excluded from the analysis due to missing weather data (at least one observation missing). The specific event examined is the cumulative rainfall and cumulative degree-day heat units from approximately June 1 to August 31 as measured on a calendar day (rather than date) to avoid leap-year problems.

Yields were detrended using a linear trend equation. Table 1 presents the sample data used in the analysis. Mean yields for corn, soybeans and hay are 125 bu./acre, 39 bu./acre, and 4.13 tonnes/acre (over two to three cuts), respectively. Yields tend to be somewhat negatively skewed, with soybeans showing the largest negative skewness. The range in yields was 43 bu./acre, 22 bu./acre, and 2 tonnes/acre for corn, soybeans, and hay. Average rainfall was 250 mm and

Table 1. Sample statistics on weather and yields

	Corn (bu./acre)	Soy (bu./acre)	Hay (tonnes/acre)	Rainfall (mm)	D-days (°F)
Mean	125.19	39.14	4.13	250.08	1532.41
Median	125.71	39.61	4.16	252.10	1534.50
Standard deviation	8.18	3.88	0.43	76.56	164.31
Kurtosis	0.68	2.84	−0.12	−0.41	2.11
Skewness	−0.13	−1.17	−0.06	0.19	−0.62
Range	43.05	22.16	2.06	331.30	957.60
Minimum	103.83	25.03	3.14	106.50	928.98
Maximum	146.88	47.19	5.20	437.80	1886.58

Correlation Matrix

	Corn	Soy	Hay	Rainfall	D-days
Corn	1				
Soy	0.493484	1			
Hay	0.340846	−0.04568	1		
Rainfall	0.09173	0.005613	0.3215823	1	
D-days	0.297817	0.302775	−0.097517	−0.20011	1

the average cumulative crop heat units was 1,532°F. The standard deviation in rainfall is approximately 76 mm and the range between the highest and lowest rainfall was 331 mm. The standard deviation and range for heat units was 164 and 957 respectively.

Also in table 1 are the correlations between the variables. Of importance are the correlations between rainfall, heat, and crop yields. With a correlation coefficient of approximately 0.30, the data indicate that the most significant factor for corn and soybeans is heat. Rainfall does not appear to contribute to corn or soybean yield variability. In contrast, hay yield is not affected to any great extent by heat, but with a correlation coefficient of 0.32, it is very sensitive to rainfall. The effect of heat on hay is minimal and negative, but still indicates that hay is perhaps more prone to heat stresses than corn or soybeans.

The correlation between heat and rainfall is low and negative. This indicates that an increase in heat units will most likely correspond with lower rainfall, but overall the relationship is not that strong.

The Cobb–Douglas equations were estimated by converting the data into logarithms. Table 2 presents the results of the least squares regressions for the detrended yields. As might be expected from examining the correlation, statistical significance of rainfall is low for corn and soybeans and high for hay. The multiple R-square measures are also low, around 0.30 for all equations. This result is expected since direct physical inputs into the equation were assumed constant, and, by construction, the nature of specific event risks was restricted to the rain and heat between June 1 and August 31. Rather than interpreting the R-square in terms of low predictive ability, it should be interpreted as the percent of total yield variability explained by the specific weather event defined as the June 1 to August 31 rainfall and heat.[3]

Table 2. Estimated regression equations (std. error in parentheses)

Dependent	Intercept	Rain	Degree-Days	R-Square
Corn	3.33	0.03	0.18	0.33
	(0.58)	(0.03)	(0.07)	
Soy	1.62	0.03	0.26	0.27
	(0.97)	(0.04)	(0.12)	
Hay	1.12	0.10	−0.03	0.31
	(0.94)	(0.04)	(0.12)	

The regression equations provide a means to assess the effects of random variables on yields. Holding all other factors constant, it is important to illustrate how effectively the equations explain the portion of annual yield volatility caused by the specific weather event. To do this, the prediction success of each equation was calculated and is reported in table 3. In table 3, variability was measured as a simple Boolean; 1 if the detrended yields increased over the previous year and 0 otherwise. The table reports the number of times that actual yields increased or decreased relative to the number of times that the equation estimate increased or decreased. For example, corn yields increased over the previous year in 25 of the 58 years. The regression equation estimate was consistent in measuring the rise and fall of yields in 20 of the 25 years for a predictive success of 80%. Likewise, of the 33 years in which yields fell, the model accurately predicted 24 of them for a total of 73%. The overall accuracy was 76% for corn, and, by similar calculations, the overall accuracies for soybeans and hay were 74% and 62%, respectively.

Table 3. Prediction accuracy of regression

	Actual Count		
Predicted Count	Up	Down	Total
	Corn		
Up	20	9	29
Down	5	24	29
Total	25	33	58
% correct	0.80	0.73	0.76
	Soybeans		
Up	22	12	34
Down	3	21	24
Total	25	33	58
% correct	0.88	0.64	0.74
	Hay		
Up	19	10	29
Down	12	17	29
Total	31	27	58
% correct	0.61	0.63	0.62

Table 4. Sensitivity of crop yields to weather variability

		Rain		
	Heat	**High**	**Mean**	**Low**
		Corn		
		437.80	250.08	106.50
High	1886.58	132.33	130.08	126.72
Mean	1532.41	127.42	125.25	122.02
Low	928.98	116.33	114.35	111.40
		Soybeans		
High	1886.58	41.91	41.19	40.12
Mean	1532.41	39.74	39.05	38.04
Low	928.98	34.96	34.36	33.46
		Hay		
High	1886.58	4.33	4.10	3.77
Mean	1532.41	4.36	4.13	3.80
Low	928.98	4.44	4.20	3.86

Although the underlying weather variables may not be stationary, the results indicate that weather does have a predictable effect on crop yield variability.

Table 4 illustrates the sensitivity of crop yields to weather variability. The cells in table 4 correspond to the estimated yields from the detrended data using the highest (438 mm, 1,886°F), mean (250 mm, 1,532°F), and lowest (107 mm, 929°F) amounts of rainfall and heat. The highest yields for corn (132 bu./acre) and soybeans (41.91 bu./acre) result from hot temperatures with lots of rain. Hay seems to thrive on lots of rain but cooler temperatures (4.44 tonnes/acre). The lowest yields resulted from low heat and rain for corn (111 bu./acre) and soybeans (33 bu./acre) and high heat and low rain for hay (3.77 tonnes/acre).

Economics and Weather Insurance

In the previous section, it was shown first that weather explains a large amount of crop yield variability, and second that specific event outcomes are predictable. Since cause and effect has been established, this section explores the design and pricing of weather derivatives. The insured can select a put option that would provide an indemnity if rainfall or heat falls below ∂_a, a call option if it exceeds ∂_b, or both (a collar). For each degree-day or millimeter of rainfall that the option is in the money, a payment of θ/unit is made. In general, the price of these contracts (in the absence of time value) would be

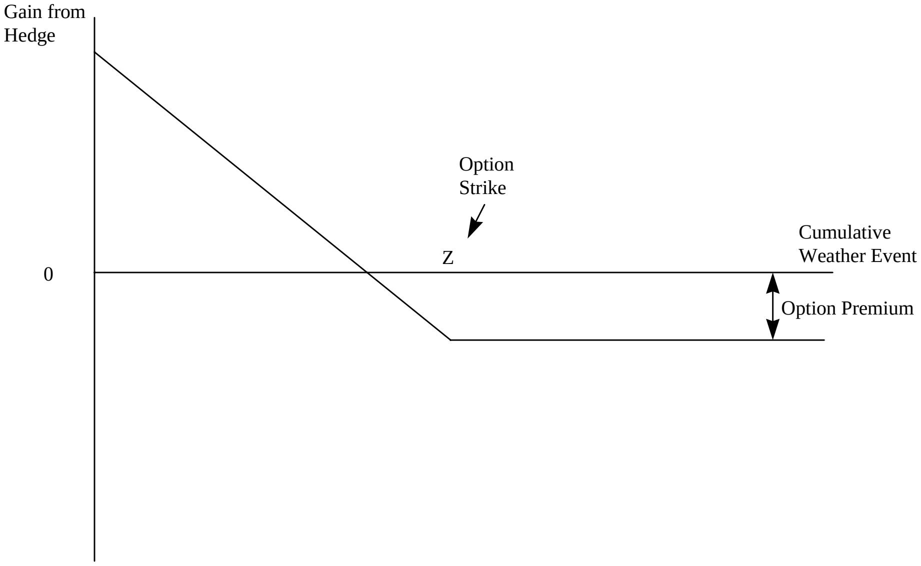
$$V_{\text{put}} = \theta \int^{\partial a} (\partial_a - \partial) f(\partial)\, d\partial \text{ for } \partial < \partial_a \tag{5}$$

and

$$V_{\text{call}} = \theta_{\partial b} \int (\partial - \partial_b) f(\partial)\, d\partial \text{ for } \partial > \partial_b. \tag{6}$$

Equations (5) and (6) rely on several factors to be priced. First, $f(\partial)$ represents the probability distribution function that describes the weather event; second, the

Figure 1. Payoff structure for European put option on weather

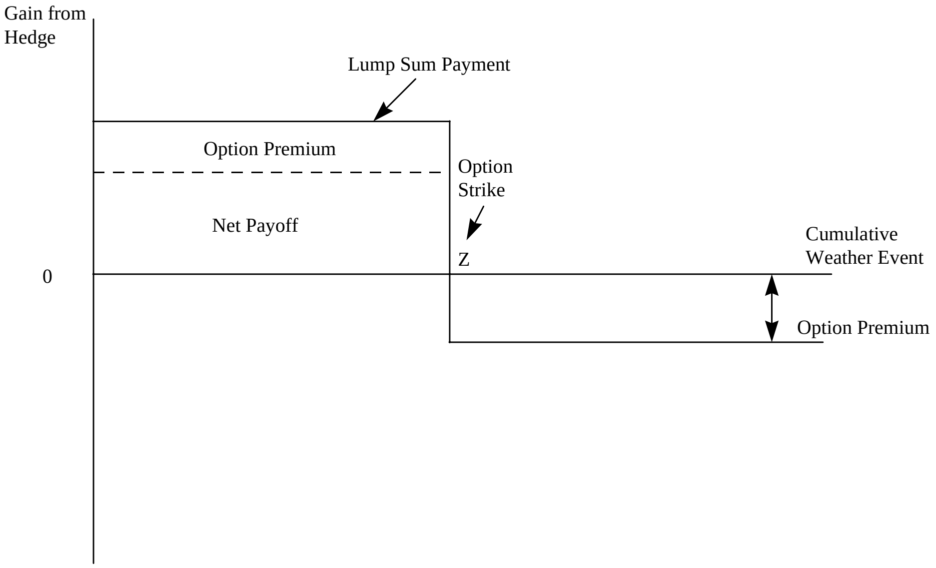


insured must have some idea of the specific event to be insured. For the put option in equation (5) the specific event is $\partial < \partial_a$, and for the call option in equation (6) the specific event is given by $\partial > \partial_b$ where ∂_a and ∂_b are strike levels. Finally, the third element is the payoff when the option expires in the money. For example if the event is based on millimeters of cumulative rainfall, then the option will pay out θ for each millimeter that rainfall is in the money. A more general way of writing the put option in equation (5) is $\theta E\{\max[(\partial_a - \partial\}), 0]$ where E is the expectation operator. Likewise the expected value of the call option is given by $\theta E\{\max[(\partial - \partial_b), 0]\}$.

Figure 1 illustrates the payoff structure for a put option. The horizontal axis describes the cumulative weather event under consideration, and Z is the strike. For example, if a weather contract stipulates a payout if rainfall falls below 5 in. (Z = 5 in.) between May 1 and August 1 with a payoff of $5,000/inch below the strike, then the end user would receive $5,000 if actual rainfall was 4 in., $10,000 if actual rainfall was 3 in. and so on.

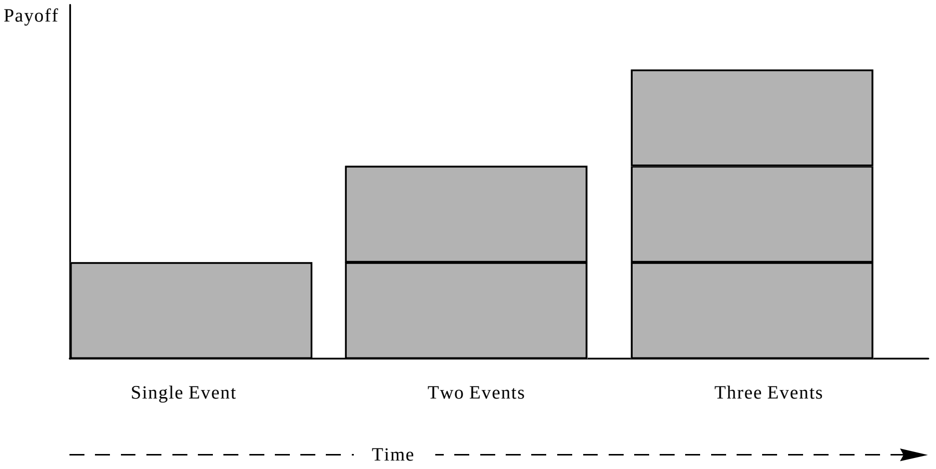
Alternatively θ may be a fixed payoff on a specific event. By setting $(\partial_a - \partial) = 1$ and $(\partial - \partial_b) = 1$ in equations (5) and (6), the options are converted to a form in which the premium equals the cumulative probability of the event happening times the lump sum payoff assigned to the event. Options of these types are similar to specific-event insurance contracts. Alternative options can be much more specific. For example the crop insurer may want to insure that cumulative degree-days exceed 1,200. If on August 31 degree-days are below 1,200, then this type of option will make a single lump sum payment. As illustrated in figure 2, the payoff function equals a loss of the premium if the event does not occur, and the total lump sum payment less the premium if the event does occur. Contracts may also be written on multiple events. For example, the insurer may want to insure that it rains at least once in any nonoverlapping 14-day period. If it does not rain,

Figure 2. Payoff structure for specific-event contract with lump-sum payment



then an event has occurred and the option would pay a lump sum of $10,000. The contract may allow for two or more events over the insured time horizon. This is illustrated in figure 3. In figure 3, the payoff from the contract increases in equal proportion to the number of events occurring within the specified time period. However, it should be noted that the likelihood of a two-event year will be less than or equal to a single-event year and the likelihood of a three-event year will be less than or equal to that of a two-event year.

Figure 3. Cumulative payoff for multiple-event weather contract



In this section, options of both types will be calculated using historical weather data. The European-type options will be priced using the "burn-rate" approach and will use historical observations to predict current risks. This implicitly assumes that history will repeat itself in one form or another.[4] Furthermore, it is assumed that the hedger is a crop insurance corporation, which faces the average yield risk in Oxford County for each of the three crops. It is also assumed for practical purposes that the weather station in Woodstock is the only weather station in the county that has complete information.[5] Based on the previous regressions, the crop insurer would face significant liabilities for corn and soybeans if heat units were below average. Likewise low rainfall would increase the liability for forage crops such as hay.

To be consistent with the equations, several strike prices for rainfall and heat units are calculated by inverting equation (1) and using the estimated parameters in table 2 and the mean values in table 1. The purpose of this calculation is to provide some relationship between yield loss and the weather event. (In practice, there is no need to find this exact relationship since the strike and the payoff are independent of crop yields.) To determine strike prices for rainfall insurance on hay, heat units are held constant at the mean $E[H]$ and critical yields, Y^*, are fixed at the mean in the first case and at 95% of the mean in the second case. The rainfall strike level is determined by $R^* = R(Y^*, E[H], A, \beta_1, \beta_2)$. Likewise the strike level for a cumulative degree-day derivative is given by $H^* = H(Y^*, E[R], A, \beta_1, \beta_2)$.[6]

The prices of European-type put option using the burn-rate methodology and assuming a payoff of \$10, 000/mm rain or \$10, 000/°F are found for the following cases:

- A degree-day strike of 1,528°F to hedge against average corn yields falling below the mean (125.19 bu./acre),
- A degree-day strike of 1,152°F to hedge against county average corn yields falling below 95% of the mean (118.92 bu./acre),
- A degree-day strike of 1,545°F to hedge against county average soybean yields falling below the mean (39.14 bu./acre),
- A degree-day strike of 1,265°F to hedge against county average soybean yields falling below 95% of the mean (37.18 bu./acre),
- A degree-day strike of 1,024°F to hedge against county average soybean yields falling below 90% of the mean (35.23 bu./acre),
- A cumulative rainfall strike of 249 mm to hedge against county average hay yields falling below the mean (4.13 tonnes/acre),
- A cumulative rainfall strike of 147 mm to hedge against county average hay yields falling below 95% of the mean (3.9 tonnes/acre).

To illustrate the pricing of specific event risks the following specific event options are evaluated for the June 1 to August 31 period:

- To reinsure against heat related stresses, payment of \$500,000 is made if average daily temperatures exceed 75°F for five days straight. Up to four nonoverlapping events are allowed.
- To reinsure against heat related stresses, a payment of \$1,000,000 is made if cumulative heat units between June 1 and August 31 is greater than 1,700.

- To reinsure against heat-related stresses, a payment of $1,000,000 is made if cumulative heat units between June 1 and August 31 does not exceed 1,200.
- To reinsure against drought related stresses, a payment of $100,000 is made if zero rainfall is recorded during any 14-day period. Up to four nonoverlapping events are allowed.
- To reinsure against drought related stresses, a payment of $1,000,000 is made if cumulative rainfall between June 1 and August 31 is less than 150 mm.

Results of Insurance Calculations

The results of the premium calculations are found in tables 5 and 6. In table 5, results for European-type options, computed using the burn rate, are presented. For the two rainfall derivatives with strikes at 249 mm and 147 mm, respectively, and payoffs of $10,000 per millimeter in the money, the estimated premiums were $299,613 and $18,290, respectively. The premiums reflect the rarity of the second event over the first (the Markov effect). For Woodstock, the likelihood of rainfall being less than 249 mm was significantly higher than the likelihood of rainfall being less than 147. In fact, the mean indemnity was paid on an average of 29.96 mm with a maximum payoff on 142.5 mm in the former case, while the mean payoff was on only 1.83 mm with a maximum of 40.5 mm in the latter case. The maximum premium that could have been paid out with the data used was $1,425,000 and $405,000. Even with the lower strike and its low probability of expiring in the money, the payoff could be quite sizable. Rare events do happen.

The degree-day put spread options based on a crop heat unit of mean daily temperatures in excess of 50°F also exhibit properties consistent with modern options pricing. For a strike of 1,545°F, the estimated premium is $696,854 with a maximum potential payoff of $6,160,200. As the specific event becomes rarer, the likelihood of the option expiring in the money decreases, as does the premium.

Table 5. European-type option calculations for rainfall and crop heat units

Item	Rainfall (mm)		Crop Heat Units (°F > 50°)				
Strike level	249	147	1,545	1,528	1,265	1,152	1,024
Mean units in the money	29.96	1.83	69.69	61.06	6.15	3.78	1.61
Standard deviation of units in the money	41.00	7.58	108.41	103.15	43.79	29.03	12.37
Minimum units	0	0	0	0	0	0	0
Maximum units	142.5	40.5	616.02	599.02	336.02	223.02	95.02
Premium ($)	299,613	18,290	696,854	610,624	61,454	37,800	16,105
Standard deviation, premium ($)	419,649	75,750	1,084,072	1,031,539	437,908	290,347	123,706
Minimum payoff ($)	0	0	0	0	0	0	0
Maximum payoff ($)	1,425,000	405,000	6,160,200	5,990,200	3,360,200	2,230,200	950,000

Table 6. Specific and multiple-event rainfall and heat unit premium calculations

	Rainfall (mm)		Heat		
Item	<150 mm Cumulative	0 mm/day	>75°F	>1,700 Heat Units	<1,200 Heat Units
# Events	1	4	4	1	1
Length of event (days)	term	14	5	term	term
Payoff/event ($)	1,000,000	100,000	500,000	1,000,000	1,000,000
Premium ($)	80,645	29,032	161,017	135,593	16,949
% 0 events occurred/year	92%	79%	74.6%	87.1%	98.4%
% 1 event occurred/year	8%	13%	18.6%	12.9%	1.6%
% 2 events occurred/year	0	8%	6.8%	0	0
% 3 or 4 events occurred/year	0	0	0	0	0

For a strike of 1,265°F, the premium falls to $437,908 with a maximum potential payoff of $3,360,200, and a strike of 1,024°F results in a premium of only $16,105 with a maximum potential payoff of $950,200.

Table 6 presents results for specific event options. The first case is an option that pays $1,000,000 if rainfall from June 1 through August 31 is less than or equal to 150 mm. The expected payoff and premium for this product is $80,645 and the event occurred with a likelihood of about 8%. The second option is a multiple-event option that pays $100,000 if there is 0 mm of rainfall in any noncontiguous 14-day period. In only 13% of the years did this event happen once, and in only 8% of the years did it happen twice. Although the option would allow for up to four events, the likelihood of more than two events was zero. The premium on this product was $29,032.

The third specific event is a heat trigger that pays $500,000 if the mean daily temperature exceeds 75°F for five days straight. This is expected to occur once in approximately 19% of the years, twice in only 6.8% of the years and not at all in about 75% of the years. The premium calculated for this product was $161,017 and the maximum potential payoff would have been $1,000,000. The fourth event is based on cumulative heat units above 1,700 at August 31 and is therefore like a call option. If the actual cumulative heat units are greater than 1,700, then a payoff of $1,000,000 is received. In only 13.6% of the years did this event happen. The premium was $135,593. The last specific event example hedges excessive cooling. If, on August 31, cumulative heat units are less than 1,200, a payment of $1,000,000 is made. This event happened only about 1.6% of the time and the premium is only $16,949.

Spatial Considerations in the Pricing of Rainfall Insurance

In this section, I examine the relationship between location and weather risk. One of the major concerns that weather insurance brokers and traders have is the relationship between the location that is being insured and the location at which the weather event is being measured. In many instances these are not the same. A case in point is the CME heating and cooling degree-day futures contracts that (as at December 1999) include only Chicago, Atlanta, Philadelphia, and Dallas. An end user in Indianapolis may buy weather insurance, and the weather insurer may in turn hedge the risk using the CME contracts for Chicago, but there will be basis risk, so the hedge ratio will likely be less than 1. Even so, heat patterns are usually extended over large areas so that there would likely be a positive correlation between the degree days in Chicago and degree days in Indianapolis. The same cannot generally be said for rainfall. Rainfall is much more sporadic and more difficult to quantify and the basis risk between (say) Indianapolis and Chicago would be much higher than the basis risk in degree days. Therefore it is critically important that rainfall derivative products have a point of reference as close to the end user as possible.

To illustrate how important this consideration is, this section examines a number of rainfall products at three distinctive locations in Ontario including Woodstock, which was discussed in the previous section. Data used are daily rainfall measures from June 1 through July 31 from 1892 to 1996 in millimeters. In addition to the highly agricultural area of Woodstock, Ontario, weather derivatives and risk characteristics are priced for Ottawa (Eastern Ontario) and Welland in Southern Ontario. Ottawa region agriculture is primarily grains and forages whereas Welland is close to the Niagara escarpment, which is home to much of Ontario’s fleshy fruit and grape growing regions.

Table 7 summarizes some key information for the three locations over this period. The average rainfall for Ottawa, Welland, and Woodstock is 174.1 mm, 145.0 mm, and 163.8 mm, respectively. The highest rainfall for each is 325.6 mm (1899), 318.8 (1937), and 308.3 (1892), and the lowest rainfall is 68.9 mm (1991), 44.5 mm (1933), and 40.4 mm (1899). The table reveals that the systematic relationship between the regions cannot be relied upon. In 1899, Ottawa recorded its highest rainfall ever, while in that same year, drought conditions produced the lowest rainfall in Woodstock. In 1937, Welland recorded its highest rainfall ever, while approximately 120 km away, Woodstock recorded rainfall close to the average. In 1991, Eastern Ontario faced a drought while in Central Ontario, above average rainfall was recorded. This summary illustrates the importance of using localized weather data, indicates the diversity (and perhaps randomness) of weather patterns across Ontario, and provides an explanation for the differences in the systematic risk of crop production across Ontario. In the following section, a number of contracts will be specified and the premiums compared by location. When specific events are being insured, it will be shown that not only do differences in regions matter for interyear comparisons, but what happens within a year is equally, if not more, important.

Table 7. Data summary 1892–1996, cumulative rainfall (mm) June 1 to July 31

	Location		
	Ottawa	**Welland**	**Woodstock**
Average	173.3	144.0	162.8
Standard deviation	51.7	54.1	56.9
High	325.6	318.8	308.0
Low	68.9	40.4	44.5
Min and Max Years			
1892	228.9	305.6	308.3
1899	325.6	138.4	40.4
1933	123.2	44.5	72.2
1937	194.7	318.8	141.6
1991	68.9	94.2	153.0

Insuring Specific-Event Rainfall Risks for Different Growing Regions

In this section, five contracts are evaluated for each of the three locations. These are:

- Option 1: Insurance that pays out $1,000 for each millimeter of cumulative rainfall below a strike of 125 mm, calculated using the burn rate method and the normal curve method.
- Option 2: Insurance that pays out $1,000 for each millimeter of cumulative rainfall below a strike of 100 mm, calculated using the burn rate method and the normal curve method.
- Option 3: Insurance that pays $10,000 per event where each event is defined as zero rainfall for 14 consecutive days, and the insurance will pay up to four separate and mutually exclusive events.
- Option 4: Insurance that pays $10,000 if the cumulative rainfall between June 1 and July 31 is less than or equal to 100 mm.
- Option 5: Insurance that pays $10,000 if the cumulative rainfall between June 1 and July 31 is greater than or equal to 275 mm.

For the first option, the specific event which triggers a payout, or puts the policy in the money, is when cumulative rainfall is less than 125 mm on July 31, and for the second option, the strike is at 100 mm on July 31.

The third option is a specific-event rainfall policy that insures two-week drought. This policy will pay $10,000 to the insured for each non-overlapping 14-day period in which no rain is recorded. The policy would expire out of the money if even 1 mm or rainfall fell at least once every 14 days. Up to four separate events will be covered under this policy, which means that the possibility of a payoff increases with extended drought.

The fourth option is a specific-event drought contract that pays $10,000 if cumulative rainfall is less than 100 mm on July 31. The option expires out of the money if rainfall in excess of 100 mm is recorded. This policy differs from the first two in that it is a single-event, single-payout policy. The payout of $10,000 is fixed and is paid out regardless of whether rainfall is 0 mm or 100 mm. In the first two cases, the amount by which rainfall is below 100 mm determines the payoff. The fifth option is a specific-event call option. Instruments of this type could be referred to as flood insurance, but in general, an end user of this instrument will have crops that are sensitive to excessive rainfall. The call option pays a fixed rate of $10,000 if cumulative rainfall is greater than or equal to 275 mm on July 31.

The results from these policies are presented in table 8. With the exception of the first two options, it would be incorrect to compare and contrast all of the policies because the underlying probability structure differs between them. However it is possible to compare the three locations, since it is the nature and design of probabilities that distinguishes them. For the first option, there is a substantial difference in the cost of insurance in Ottawa, Welland, and Woodstock. At a 125-mm strike, the value of the option is equal to $4,142 in Ottawa and $12,819 in Welland. The maximum payoff that would have been made since 1892 is $84,600 for Woodstock, $80,500 for Welland, and $56,100 for Ottawa. The results illustrate the significance of how events are distributed. For example, even though Woodstock would have recorded the largest payoff, the insurance costs are still lower than Welland.

The zero rainfall 14-day event option is priced at $952, $2,039, and $1,810 for Ottawa, Welland, and Woodstock, respectively. There is a 91.4% chance that no event will occur in Ottawa, while an 81.6% chance of no event is recorded for Welland. There is nearly a 2% chance of two events occurring in Welland, a 3% chance of two events in Woodstock, and a 1% chance of two events in Ottawa. In general, significant drought is a rare event, which occurs about once a decade only. However, depending on location, the frequency and distribution of these rare events can vary significantly.

The fourth option is a less extreme drought policy than that above, but its structure is different as well. At July 31, the chance of having less than 100 mm of accumulated rainfall is very rare in Ottawa, where the premium would only be $571. Welland is most drought prone with a cost of $2,621, and the cost of the policy in Woodstock would be $1,714.

Finally, the fifth option illustrates how insurance can be used to protect against excessive rainfall. With a premium of $571, Woodstock appears to have the greatest likelihood of excessive rain, with Welland and Ottawa facing costs of only $388 and $381, respectively. In contrast to the fifth option, there is a much greater likelihood of too little rain than too much rain.

The important observation from exploring this limited number of insurance products is the verification that a uniform rainfall insurance policy will not be successful, at least on an actuarial basis. The risks by location are significantly different, as one would expect in an area where different and varied macro- and microclimatic conditions prevail. Of the three locations illustrated above, Welland is the most drought prone, and therefore insurance or derivative products targeted towards this region would be more highly priced than the other two regions. Ottawa is the least likely area to suffer extreme drought conditions. It is also important to recognize that different climatic conditions can affect different locations at the same time. Recall from table 7 the observation that in 1899, Ottawa

Table 8. Estimated premium and payoff results for insured events, June 1–July 31

Description	Ottawa	Welland	Woodstock
Drought insurance put option @ $1,000/mm; strike = 125 mm			
Burn rate model premium	$4,142	$12,819	$9,100
Maximum payout (1892–1996)	$56,100	$80,500	$84,600
Drought insurance put option @ $1,000/mm; strike = 100 mm			
Burn rate model premium	$968	$4,372	$3,524
Maximum payout (1892–1996)	$31,100	$55,500	$59,600
Drought insurance; insure specific event of 0 mm/day for 14 days; maximum 4 events; $10,000/event			
Premium	$952	$2,039	$1,810
Standard deviation of payout	$3,259	$4,506	$4,553
Maximum payout	$20,000	$20,000	$20,000
Chance of 0 events	0.914	0.816	0.848
Chance of 1 event	0.076	0.165	0.124
Chance of 2 events	0.010	0.019	0.029
Chance of 3 events	0.00	0.00	0.00
Chance of 4 events	0.00	0.00	0.00
Drought insurance; insure specific event of <100 mm cumulative rainfall; payout = $10,000			
Premium	$571	$2,621	$1,714
Maximum payout	$10,000	$10,000	$10,000
Flood insurance; insure specific event of <275 mm cumulative rainfall; payout = $10,000			
Premium	$381	$388	$571
Maximum payout	$10,000	$10,000	$10,000

recorded its wettest season on record, Woodstock its driest, and in that same year Welland was near average. The obvious caveat is that even though some weather conditions can be highly correlated among locations, this is not a rule that can be relied on with any actuarial precision.[7]

Discussion and Conclusions

An emerging market for weather-based derivative products could offer new hedging possibilities for agricultural production. Unlike commodity hedges using futures contracts and options on prices, the use of weather derivatives provides a market mechanism for insuring against output. The efficacy of weather derivatives on rainfall or heat depends on a number of factors, the most important of which is the identification of specific risks. In this paper, daily rainfall and temperature data from 1935 to 1996 at Woodstock, Ontario, was examined. In the first part of the paper, cumulative rainfall and cumulative degree-days above 50°F were correlated with average county yields. Using a Cobb–Douglas production function, it was shown that corn and soybeans are more sensitive to low temperatures, while hay was more sensitive to low rainfall. The results indicate that specific-event weather conditions can contribute significantly to crop yield risk and thus weather insurance/derivatives can have a significant role to play in managing agricultural production risks.

It was also shown that pricing weather derivatives on large area would be foolhardy. Using historical data at Woodstock, Ottawa, and Welland, a number of option products were evaluated. The results clearly show that the pricing and payoff probabilities must be location specific, and efforts must be made to minimize basis risk. One promising approach that requires further study is to triangulate a particular (farm's) location to three or more weather stations and weight each weather station record by the triangulated distances. Using such an approach, a crop insurer could provide farm level weather insurance while taking an opposite position in the reinsurance market. In addition, such an approach would virtually eliminate all forms of moral hazard and adverse selection.

That weather events can be tied to production risk is important because it implies that new weather-based derivative instruments can be designed. With these products, the underlying risk is not in crop yield variability but in the source of that variability. In terms of specific event risks yield variability is the effect, so it is not unreasonable to insure the cause directly. The advantage to a crop insurer or reinsurer is that a payoff based on such an objective measure does not require any proof of damage.

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Endnotes

[1] For example, a contract based on crop heat units (or growing degree-days, GDD) might be written as "The Company will insure from May 1, 1999 to August 31, 1999 that there will be 1000 or more Crop Heat Units at the Environment Canada weather station located at Woodstock Ontario. Every day where the average temperature exceeds 50 degrees Fahrenheit, there will be {average temperature −50} heat units for that day."

[2] We could also have used a quadratic function for this part of the analysis. However, upon estimation of the actual parameters, we found that the quadratic function was not a good a fit while the log-linear Cobb–Douglas form was. See Kaufmann and Snell for a quadratic estimating equation that reasonably explains the effects of weather on yield. Since they used a quadratic form, they were also able to identify optimal conditions along the estimated growth-yield curve. Their model does not appear to include rainfall–heat interaction; however, as will be discussed later, this may not be that important.

[3] There are, of course, many regressions. For example, one could regress yields against rainfall in the two-week period around the first of July, or heat for the month of August. It is extremely unlikely that any single regression equation will be flexible enough to capture all of the specific event risks that crops face.

[4] Further complicating the issues is the appropriate approach to use in pricing weather derivative products. As indicated above, much of the current pricing is based on historical retrospection that assumes that weather history will repeat itself. This approach is common to the insurance industry and is referred to as the burn-rate approach. In the alternative, several recent working papers have appeared that use various approaches to pricing weather derivatives using Brownian motion as the underlying stochastic process; however, there is no consensus on which approach to use except that because weather is a nontraded asset, conventional Black or Black–Scholes models are inappropriate (Cao and Wei; Dischel; Pirrong; Turvey). All of these models require the existence or construction of a weather index that evolves randomly over time.

[5] This is quite critical, especially for rainfall insurance. Currently, Agricorp, Ltd., the provincial crop insurer, offers a rainfall-based forage plan that requires insureds to record weather on their own farm. This is then entered into a computer program and the yield is simulated. Indemnities are paid on the variance in the simulated yields. However, the program faces some problems of which moral hazard and errors in measurement are significant. The move to rainfall derivatives with a strike based on rainfall rather than yields has some attractiveness since damage does not have to be proven. However, the problem of disparate rainfall is still a significant issue. One solution would be to triangulate rainfall from a number of rainfall stations throughout the county, thus creating a matrix with each intersecting point representing a weighted average (by distance) of the various weather stations.

[6] For example, from equation (1), $R^* = \{0.8 \times E[Y]/aH^{\beta 1}\}^{1/\beta^2}$ will find the amount of rainfall associated with 80% of detrended average yields. It is worth reminding the reader that in practice, these breakpoints do not have to be calculated. For the purposes of this paper, the breakpoints provide useful guidelines for establishing option strike prices.

[7] One can imagine many situations where incomplete data at one location may require regression or correlation analysis with a second location in order to extrapolate rainfall. If, under these circumstances, systematic risk is low and the extrapolation is used to calculate premiums, it may be prudent to use Monte Carlo or other simulation techniques to estimate the premiums.

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