ALTERNATIVE HEDGING STRATEGIES IN MAIZE PRODUCTION TO COPE WITH CLIMATE VARIABILITY AND CHANGE

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Abstract

Climate change with increasing climate variability is likely to alter risks in agricultural production. The effectiveness of using weather derivatives to hedge against drought risks for rain-fed grain maize production was investigated for current (1981-2003) and future (2070-2100) climates in Switzerland. The climate change scenario was extrapolated from results of a regional climate model (HIRHAM4) based on the IPCC A2 emission scenario. In addition, a sensitivity analysis was performed by varying the mean and variance of the initial probability space for the seasonal precipitation sum. Profits and risks with and without hedging were compared using the analogy of the value-at-risk measure (VaR), i.e., a quantile-based measure of risk. A Monte Carlo chain composed of different models was used, with each model consisting of functions translating weather variables into the stochastic distributions for grain yield and economic returns. Depending on location, hedging reduced VaR to a variable degree under both current and future climatic conditions, with a considerable basis risk due to spatial heterogeneity of precipitation. The results also showed that hedging might provide a valid risk transfer since loading of 90 to 240% of the fair premium can be paid to obtain a hedged situation with improved outcomes relative to the business-as-usual reference. However, due to the uncertainty attached to climate scenarios and a strong bias in precipitation scenarios for the European alpine region, application of weather derivatives would require continuous re-equilibration and recalculation of the premiums. Depending on local conditions, the fair premium of a specific contract for hedging against weather risks in grain maize production may vary by a factor of two to four over the 70-year period considered. This represents a substantial uncertainty for both the underwriter (farmer) and the institution writing the contract.

Keywords

Climatic change, climate risks, drought, maize production, weather derivatives, hedging

1 Introduction

Current climatic conditions in central Europe are favourable to crop production. However, projections of future climate conditions (FUHRER ET AL., 2006; BENISTON and DIAZ, 2004) with their effects on the hydrology of alpine basins (JASPER ET AL., 2004) and more frequent droughts (CALANCA, 2007), together with the continuing rise of human water demand (SHIKLOMANOV, 2000), emphasize the need to minimize agricultural water use as part of optimal resource allocation (FAO, 2002). Recent extremes, such as the summer of 2003 (SCHÄR ET AL., 2004) with estimated losses in the agricultural sector of around 12 billion US$ in Europe (SWISS RE, 2004) and 400 million US$ in Switzerland alone (KELLER and FUHRER, 2004), demonstrated the importance of climatic extremes. To minimize yield losses during extreme years, implementation of conservative strategies for water use, or implementation of irrigation systems would be needed.

Alternatively, risk management involving hedging with relatively new financial instruments, the so-called "weather derivatives" (HULL, 2002; JEWSON AND BRIX, 2005; ZENG, 2000), could be envisioned in Europe. Conceptually any weather variable can be indexed (AGARWAL, 2002); contracts based on precipitation have been described in the literature (AGARWAL, 2002; ASSELDONK, 2003; CAO ET AL., 2004; MARTIN ET AL., 2001; SKEES ET AL., 2001; TURVEY ET AL. 2006; VEDENOV and BARNETT, 2004), but more often, temperature-based indices have been used (ALATON ET AL., 2001, ASSELDONK, 2003; CAO and WEI, 2004; LEGGIO and LIEN, 2003; OETOMO and STEVENSEN, 2005; RICHARDS ET AL., 2004; TAYLOR and BUIZZA, 2004, 2006; TURVEY ET AL., 2006; ZENG, 2000).

The aim of this exploratory study was to evaluate the effectiveness of weather derivatives in hedging against risks associated with a shortage of precipitation for grain maize (*Zea mais* L.) production in Switzerland. The approach used was to compare a reference situation of conventional rain-fed cultivation, which reflects the current Swiss standard, with the alternative scenario represented by rain-fed cultivation backed up by risk management using weather derivatives. The efficiency of the two strategies was compared with a concept similar to the value-at-risk metric (ARTZNER ET AL., 1999), broadly used by finance practitioners due to its relatively simple concept and its ability to summarize the risk of a portfolio as just one number. From a statistical point of view, this approach is a quantile analysis of the distribution of profits simulated with a Monte Carlo chain (MC) to translate the weather variables into stochastic distributions for maize yield and associated economic returns. This allows handling the mean-variance framework for risk analysis in the situation where production costs are correlated with crop yields, and where the distribution of both the variables and the profits are skewed, not Gaussian, and censored at critical thresholds. For the study, specific locations in Switzerland were used, but to broaden the scope, a sensitivity analysis was performed by varying the mean and variance of the initial probability space for the seasonal precipitation sum.

For the agricultural sector limited availability of yield or weather time-series often constrains the application of regression fitting to calculate the loss function, and correlations between yield and weather variables may be too weak (even if significant) for hedging purposes. As an alternative, we derived the loss function using a stochastic crop growth model with a minimum set of parameters required (TORRIANI ET AL., 2007b).

2 Methods and Data

2.1 Production costs

Costs for maize production were estimated with the methodology described by LIPS and AMMANN (2006) with census data for representative Swiss farms covering the years 1975 to 2004 (FAT, 2004) (Table 1). Variable costs associated with machinery, cleaning, and drying dominate fixed costs generated by interest/rent or administration. A fixed grain price of 450 CHF t^{-1} was used since reference prices vary each year based on projected production, expected quality of crop, and decisions concerning customs taxes and import policies, but over the past five years, the price has varied only by +/-5% (SwissGranum, available at: http://swissgranum.ch).

Table 1. Summary of costs and revenues (in CHF) for different yield levels.[*)]

	Level of grain yield (t ha^{-1})				
	7.5	8.5	9.5	10.5	11.5
Costs ha^{-1}					
Seeds	272	272	272	272	272
Fertilizer	249	249	249	249	249
Plant protection	217	217	217	217	217
Cleaning and drying	805	912	1019	1127	1234
Hail insurance	61	69	77	85	93
Other direct costs	7	7	7	7	7
Labour costs	764	764	764	764	764
Machinery costs	1345	1359	1368	1368	1368
Land value	718	718	718	718	718
Interest rate costs	38	40	43	46	49
Other indirect costs	728	728	728	728	728
Income					
Grain price t^{-1}	450	450	450	450	450
Producer benefits	3375	3825	4275	4725	5175
Other benefits	41	41	41	41	41
Direct payments	1600	1600	1600	1600	1600
Profit ha^{-1}	-187	130	453	785	1116

[*)] Source: Data from Lips M. and Ammann, H., Agroscope ART Taenikon, Switzerland

2.2 Profits

A Monte Carlo chain was used to develop profits with and without hedging. A sample of n = 300 x 10^3 was drawn from the gamma probability density function (PDF) of seasonal rainfall. This sample size was necessary to reach a precision of 0.01 t ha^{-1}. The distribution of profit B (CHF ha^{-1}) for grain maize production without hedging was calculated as,

$$B = Yp_m - c(Y) \tag{1}$$

with grain yield Y (t ha^{-1}) sold at a price p_m (CHF t^{-1}), and having the cost function $c(.)$ (CHF ha^{-1}) as the first-degree polynom ($21.15Y + 3471$; $r^2 = 0.94$; RMSE = 7.84 CHF ha^{-1}) providing costs depending on yield level Y (see Table 1). Profit with hedging B_{wd} (CHF ha^{-1}) was calculated from profit for conventional production (B) and from considering a number of weather derivatives h (contracts ha^{-1}) with a premium of c_{wd} (CHF $contract^{-1}$) and a payoff P (CHF $contract^{-1}$). The producer would pay a constant amount hc_{wd} to the writer for an indemnity of hP. Analytically, this can be expressed as,

$$B_{wd} = B - hc_{wd} + hP \tag{2}$$

Here, the contract was tailored to one hectare and thus h=1.

The effectiveness of hedging was evaluated on the basis of a quantile-based risk-measure of the profit distribution (ARTZNER ET AL., 1999; HULL, 2002), i.e. the value-at-risk measure (VaR), as an alternative to the abstract risk preference and utility functions (i.e. MARTIN ET

AL. 2001). The notation θ-VaR was used where θ is the confidence level for the corresponding α-quantile, thus θ=(1-α). Accordingly, the 95-VaR refers to a probability of PR{B≤95-VaR} =5%. A second parameter defining VaR is the duration in days over which the risk is evaluated. Maize harvest occurs once per year and thus only year-to-year variations were considered. Therefore, a single year was the smallest discrete step of our analysis.

Results of the monetary balance were placed in mean-variance plots for a sensitivity analysis performed by changing (i) mean rainfall from zero to 600 mm, and (ii) the second moment of the distribution from zero to 250 mm. Production costs, yield levels, and profits were adjusted for each condition.

2.3 Pricing

The premium was calculated as the unconditional expectation (E) of payoff and discounted at the risk-free rate r_t (HULL, 2002), although different discount rates reflecting the market price for risk have been proposed (TURVEY, 2002; DAVIS, 2001). The payoff distribution was simulated with Monte Carlo methods from the rainfall distribution. It was assumed that all underlying variables have zero systematic risk and thus the statistical measure of risk was taken as an alternative to the risk-neutral approach (BLACK and SCHOLES, 1973; MERTON, 1973). Direct comparison is conventionally done after converting the future value into the net present value by discounting at $d=e^{-r_t t}$. The option is purchased at date t_1 and cashed at maturity date $t_2>t_1$, separated by t (years). The rainfall index x is defined as the integration of the daily precipitation (mm) (see (12)). The put payoff function $p()$ pays an amount D (CHF mm^{-1}) for each mm of accumulated rainfall below a strike K (mm), following JEWSON and BRIX (2005):

$$p(x,K) = \max(0, D(K-x)) \quad (4)$$

As an example, if K = 200 mm and D = 100 CHF mm^{-1}, then for an index value of x = 150 mm at the end of the accumulation period (at maturity), the put will pay $5000d_t$, or 4925 CHF for r_t=0.02 and T=0.75. Thus the option value v becomes:

$$v(x,t) = e^{-r_t t} E[p(x,K)] \quad (3)$$

One contract costs v (CHF contract^{-1}), and in the long-term a farmer can expect (in a probabilistic context) to receive back the same amount discounted at d_t. The risk-free rate is approximated at 2% from the historic LIBOR rate for the 9-months maturity duration over the years 1997-2005 (LIBOR, 2006). As mentioned previously, grain prices can be assumed to be constant and price volatility equal to zero (as may the covariance between grain prices and indemnities), thus not affecting the pricing procedure (DAVIS, 2001). We assumed no transaction costs outside of the interest rates on capital.

2.4 Structured product

The payoff function of the standard put is linear, but sometimes it is more interesting to obtain non-linear payoffs that better fit the hedge's purposes. In this case, the goal is to create a synthetic put with a concave payoff function mirroring the function of yield loss. Here we considered a structure of standard puts with equal tick size and equally spaced strikes. The latter assumption aims at imitating existing markets since the advantage is to rationalize the process of writing standard instruments that can be used for multiple purposes among industrial sectors, thus possibly attracting more liquidity in the weather derivatives market. This assumption is not primary, however, since trading strategies aimed at replicating synthetic options are possible. The structured product payoff function *s* is then:

$$s(x) = \sum_{i=1}^{m} w_i p(x, K_i) \tag{5}$$

For a general case where w_i is the weight of the put options to be purchased at each strike K_i and separated by an offset *O* (mm), the total quantity of options *m* becomes:

$$m = 1 + floor\left(\frac{K_m - K_{i=1}}{O}\right) \tag{6}$$

The quantity of options that needs to be purchased at each strike is equal to the slope of *l(x)* minus the quantity purchased until then for higher strikes, with the initial condition of K_m=1. Thus, solving iteratively beginning from the second topmost strike:

$$w_i = \frac{d}{dx} l(K_i) - \sum_{j=i-1}^{m} w_j \tag{7}$$

A final assumption was that w_1, i.e. the weight for the put with the smaller strike, is equal to the difference between the sum of all quantities purchased until then and the slope at the intercept:

$$w_1 = \frac{d}{dx} l(0) - \sum_{j=2}^{m} w_j \tag{8}$$

2.5 Crop model

The stochastic crop growth model was built following the work of MONTEITH (1972 and 1977). We described yield as the product of radiation use efficiency ε_{pot}, which is a crop-specific parameter, global radiation *I* (W m^{-2}), and a series of limiting factors η_i:

$$Y = \varepsilon_{pot} I \prod_i \eta_i \tag{9}$$

The normalized limiting factors η_i considered here are water stress η_w (-) and vapour pressure deficit (VPD) limitation η_t (-), the latter representing the indirect effect of temperature on yield (TORRIANI ET AL., 2007b). The relationships were fitted to results of simulations with the deterministic crop growth model CropSyst (STÖCKLE ET AL., 2003), described in TORRIANI ET AL. (2007b), using perturbed meteorological observations to widen the range of climatic conditions beyond the range of observed data. Mean VPD was extended between 0 and 25 hPa to reflect dryer and wetter atmospheric conditions. Rainfall was reduced over a range of 0 to -60%. Simulations were performed for a single soil type with 38% clay, 36%

silt, 26% sand, and 2.6% of soil organic matter – a soil type characterized by a good water retention capacity.

The increase in CO_2 concentration positively affects productivity through effects on canopy resistance to water vapor transfer and carbon assimilation (*cf.* FUHRER, 2003), but the magnitude of the CO_2-stimulation of yield is debated (see LONG ET AL., 2006), especially for C4 crops like maize. Therefore, the VaR analysis was performed without considering increased (CO_2) in the climate change (CC) scenario.

2.6 Meteorological data

The baseline for 1981 to 2003 consisted of the observed meteorological data provided by the Swiss Federal Office of Meteorology and Climate (MeteoSwiss). The weather stations at Magadino (MAG: 46°10' N, 8°53' E, 197 m above sea level), Schaffhausen (SHA: 47°41' N, 8°37' E, 437 m) and Waedenswil (WAE: 47°13' N, 8°41' E, 463 m) were used to represent lower altitudes, with MAG also representing the region south of the Alps. The locations of Beznau (BEZ: 47°34' N, 8°14' E, 327 m), Kloten (KLO: 47°29' N, 8°32', 436 m), Leibstadt (LEI: 47°36' N, 8°11' E, 341 m), and Reckenholz (REH: 47°26' N, 8°31' E, 443 m) located along a north-south axis were used to evaluate the spatial heterogeneity of rainfall (i.e. the basis risk). Application of the hedging strategy was carried for WAE, MAG and SHA.

2.7 Climate model and climate change scenario

The stochastic framework was based on the rainfall index x as the independent variable, and radiation and air vapour pressure deficit (*VPD*) as the dependent variables. Linear covariance between weather variables was assumed and a stochastic error was added as a normal term $N(0, \sigma^2)$ with zero mean and a suitable standard deviation σ reflecting the observed spread of the indices:

$$\langle I \rangle \approx D_I(\langle x \rangle) + N(0, \sigma_I^2) \tag{10}$$

$$\langle VPD \rangle \approx D_{VPD}(\langle x \rangle) + N(0, \sigma^2{}_{VPD}) \tag{11}$$

Here, *D()* is the deterministic linear term for the corresponding variable. Defining the parameters of the climatic model required records of precipitation (mm), mean temperature (°C), *VPD* (hPa), and global radiation (W m^{-2}), corrected for data inconsistency but without homogenization (ALLEN ET AL., 1998).

The rainfall index x is defined as the integration of the daily precipitation P (mm) over the accumulation period from - and including - the first (t_1) to the last ($t_2 > t_1$) day considered:

$$\langle x \rangle = \sum_{i=t_1}^{t_2} P_i \tag{12}$$

The operator $\langle \ldots \rangle$ means that integration over the accumulation period was used for rainfall and averaging was used for the other variables. The chronological limits t_1 and t_2 were kept constant each year, although in reality they should reflect crop phenology as a function of thermal time (growing degree-days, °C-days). Phenological dates were determined through simulations with CropSyst (see above). The t_1 limit was set at 400 °C-days after the sowing date (May 10, or the day of the year (DOY) 130), i.e. shortly before the beginning of the flowering phase and nearest to the start or end of a month in order to have a full month's accumulation. The t_2 limit corresponds to the completion of maturity at 1250 ^{o}C-days, which is a crop-specific parameter and was previously calibrated with observations. The time of maturity varies from year-to-year by up to 1-2 months depending on region and variety, but here we used a mean DOY of 273.

The positive temperature trend in the CC situation was considered by inducing a shift by -30 days in the sowing date (TORRIANI ET AL., 2007a,b). This means that the moment estimator used to adapt the rainfall gamma PDF for CC conditions accounted for this shift in growing season, but parameters for both the deterministic and stochastic terms were not updated in spite of a possible change in the relationships between weather variables.

The CC scenario referred to the years 2071-2093 and was derived from the observed baseline (1981-2003) by shifting the observations as described in TORRIANI ET AL. (2007a); it included changes in the inter-annual variability along with shifts in mean monthly values. CC anomalies were extrapolated from the regional model HIRHAM4 (CHRISTENSEN ET AL., 1998). Initial and boundary conditions for running the regional model were extracted from the atmospheric circulation model HadAM3H (POPE ET AL., 2000) and were driven by the output of the ocean-atmosphere coupled with the global climate model HadCM3 (JOHNS ET AL., 2003). The A2 emission scenario (NAKICENOVIC and SWART, 2000) was considered as representing an upper limit for emission projections.

2.8 Loss function and basis risk

Ideally, the loss function representing a relationship between yield and the underlying variable should have defined parameters for each location and corresponding climatology. Here we used a single function with parameters defined using the results of the stochastic model sensitivity analysis, obtained by changing the shape of the rainfall distribution α (-) and the scale parameter β (mm) with their moment estimators according to TORRIANI ET AL. (2007a). The explicit form of the loss function used was similar to that of the water stress model (TORRIANI ET AL., 2007b) since it allows for the easy differentiation necessary to calculate the weights of the structured product in (7) and (8):

$$l(x) = \tanh\left(k \frac{x}{ET_{pot}(x)} \right) \tag{13}$$

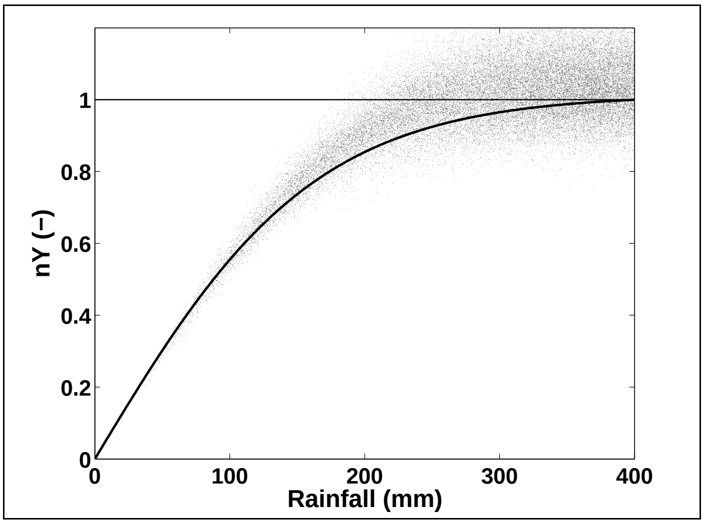
Potential evapotranspiration (ET_{pot}) was used as a function of rainfall (CALANCA, 2004; TORRIANI ET AL., 2007b), and k (CHF) as a specific fitting parameter.

Another point that may limit the effectiveness of a hedging strategy is the uncertainty associated with spatial heterogeneity of rainfall, defined as the basis risk. If a site is distant from the weather station where the reference index was measured, the amount of rainfall may differ substantially from the reference quantity, and the correlation between loss and reference index may decline. We used a simple quantification of the spatial heterogeneity for rainfall by comparing the correlation coefficient for the payoff of the structured product between a reference station (Zurich) and various nearby weather stations to determine the change in correlation as a function of distance from the reference station.

3 Results

The hedging contract covers a precipitation range useful to insure the production from zero up to the mean yield level in Switzerland of about 10 t ha^{-1}. Grain yield reaches a maximum value around 400 mm and then starts to decline due to limiting radiation and temperatures associated with unfavourable wet conditions (Fig. 1). This results in a maximum liability and thus a maximum payoff of the structured product of 4637 CHF contract^{-1}. The parameters of the loss function were defined by fitting (13) data from the Monte Carlo model with the least squares method (a = 4833 CHF contract^{-1}, c = 0.004851 mm^{-1}, r^2 = 0.98, RMSE = 225 CHF, *n* = 300 x 10^3).

Figure 1: Normalized loss function (full curve) and results of the stochastic yield model for the sensitivity analysis.



The optimum weight w_i for each option necessary to build the structured product was obtained iteratively by solving (7) and was used to fit the inverse image of the loss function (Fig. 2). It gives a total number of 23 options between 100 and 400 mm, with the weight for the option at strike 350 mm equal to zero, i.e. this strike is not required (Tab. 2).

Figure 2: Inverse image of the loss function (solid line) and the payoff for the structured product (dashed line) (*s*(<x>)). m(<x>) is mean rainfall.

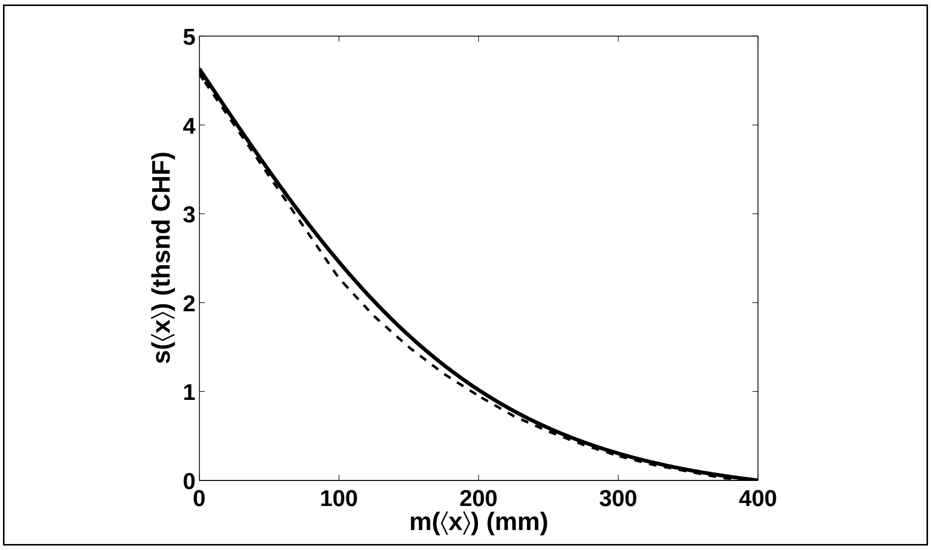
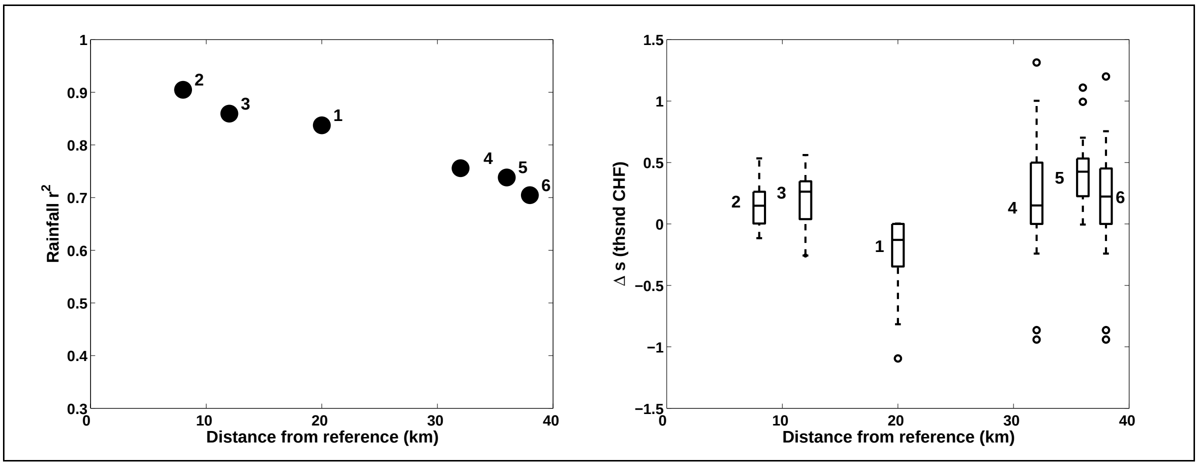


Table 2: Weights of each put structuring the product.

	Strike level (mm)												
	100	125	150	175	200	225	250	275	300	325	350	375	400
w_i	6	2	2	2	2	2	1	1	1	1	0	2	1

The basis risk associated with the spatial heterogeneity of rainfall was evaluated both in terms of the correlation between the seasonal rainfall (Fig. 3) and the difference in the payoff between the reference site and the target locations. The correlation for rainfall showed a proportional decay that remained above an r^2 of 0.7 (with $p<0.05$ in all cases) for distances of up to 50 km. The r^2 for the payoff was slightly lower, yet above 0.6 for a distance up to 15 km (not shown), and the basis risk in absolute terms remained below 500 CHF contract^{-1} for distances up to 15 km, with a mean of 200 CHF contract^{-1}, but the maximum difference could reach 1400 CHF contract^{-1} for distances exceeding 15 km. These results require further analyses, considering possible spatial anisotropies and using an improved spatial interpolation.

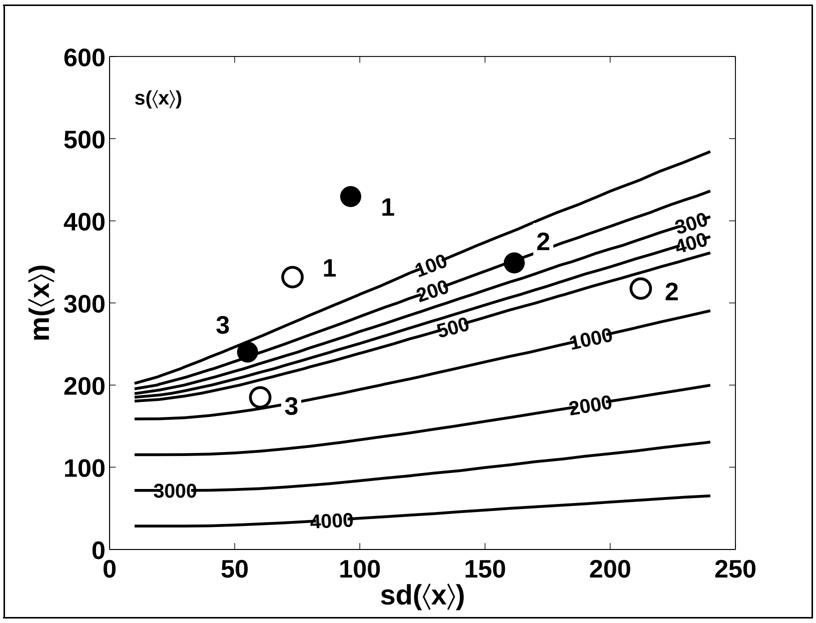
Figure 3: Change in r^2 for rainfall (left) and absolute difference in payoffs *s* (reference - station) as a function of distance from the reference station (Zurich - SMA) (1 WAE, 2 REH, 3 KLO, 4 BEZ, 5 SHA and 6 LEI) for 1981-2003. In box plots, whiskers extend to 1.5 x the quartile range, the box represents the upper/lower quartile and median, circles represent outliers.



The sensitivity analysis for the fair premium revealed an increase from the baseline climate to CC conditions for MAG from 210 to 620 CHF ha^{-1}, and for SHA from 160 to 783 CHF ha^{-1} (Fig. 4). The fair premium at WAE was nearly zero due to the mean rainfall level above the upper put strike, i.e., the weather derivative is usually "out-of-the-money."

The comparison between the situations with or without hedging showed that hedging was effective in reducing the VaR gradient along the variance axis (Fig. 5), which may be expected from this type of instrument. MAG located south of the Alps and SHA north of the Alps are both characterized by climates which favour water stress conditions in maize (TORRIANI ET AL., 2007b), and thus the system is sensitive to rainfall variability. Under CC conditions the conventional 95-VaR dropped by 130% at MAG and by 160% at SHA (Tab. 3). However, the results showed that hedging remained effective even if the premiums under CC conditions increased (Fig. 4). In contrast, at WAE hedging was not effective since there was negligible yield reduction due to water stress (about 5%, TORRIANI ET AL., 2007b) and due to little rainfall variability in both the baseline and CC scenarios. For soils with a lower water retention capacity than assumed here, the risk for water stress would be higher and thus possibly justify the hedge, but the pricing of the structured product may still be difficult. A further limitation of weather options at WAE is a premium lower than 10 CHF contract^{-1} due to the out-of-the-money situation (when the seasonal rainfall is less than ~400 mm).

Figure 4: Sensitivity analysis: premium of the structured product (CHF contract^{-1}) in relation to the mean rainfall level and standard deviation for WAE (1), MAG (2) and SHA (3) for the baseline (full circles) and CC scenario (empty circles). Note the changing spacing between isolines for values below 1000 CHF. m(<x>) is mean and sd(<x>) is standard deviation.

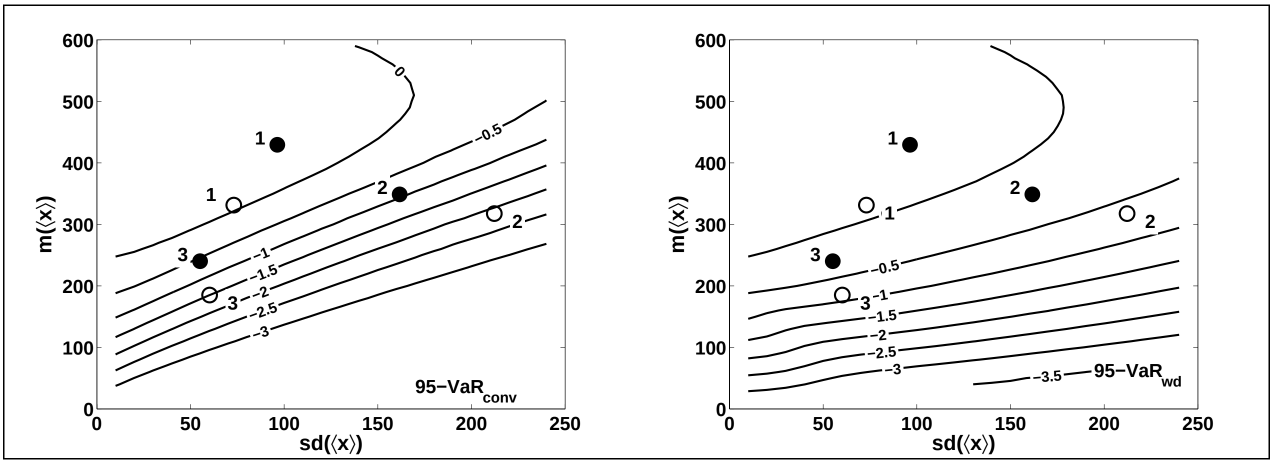


The difference between conventional and hedged VaR can be used to determine how much a premium can be increased above the fair premium before reaching the risk level of conventional risk management, thus possibly providing a simple quantification of how much a farmer would be willing to pay for the hedge and, conversely, how much a financial institution may charge to cover its exposure. At MAG, the fair premium can be loaded up to 240% before bringing the situation near the conventional one, whereas at SHA the fair premium can increase by 93%. The smaller potential at SHA is caused by lower mean profits expected for producing maize (baseline: 260 CHF ha^{-1}) in contrast to the slightly higher grain yield and gains at MAG (baseline: 420 CHF ha^{-1}).

Table 3: Fair premium and 95-VaR (rounded to 10) for baseline and CC scenario.

	Premium (CHFcontract^{-1})	95-VaR$_{conv}$ (CHF ha^{-1})	95-VaR$_{wd}$	90-VaR$_{conv}$	90-VaR$_{wd}$
Baseline					
MAG	210	-920	-200	-460	-70
SHA	160	-570	-260	-370	-160
CC Scenario					
MAG	620	-2130	-640	-1580	-500
SHA	780	-1500	-840	-1230	-740

Figure 5: Sensitivity analysis for 95-VaR value (in thousand CHF ha^{-1}) for the conventional (left) and hedged (right) management with rainfall statistics for baseline (full circles) and CC conditions (empty circles) at WAE (1), MAG (2) and SHA (3). m(<x>) is mean and sd(<x>) is standard deviation of rainfall.



4 Discussion and Conclusions

Weather derivatives are effective instruments for hedging against the risk associated with weather variability under today's climate, and will be even more effective under projected future climates. One assumption of this work was to calculate the premium of the contract with the statistical measure of risk (fair premium), implying that there is no loading for the costs and risks endorsed by the financial institution writing the contract. This presents an unrealistic situation, except if a government supports the hedging strategy and covers the risk exposure and expenses. Nevertheless, we find that even when considering premiums that are at least 100% higher than the fair premium, hedging remains attractive for maize producers when compared with conventional risk management, both for baseline and climate change assumptions, thus allowing the financial institution to cover its expenses and eventually the uncertainties related to climate change. However, the seller cannot freely charge a premium; rather, a Pareto equilibrium should be reached by parties, that is as well dependent on the supply and demand mechanisms of the market.

In this study, we used a modeling approach to determine weather-yield loss relationships instead of traditional regression methods based on observed data. The advantage is that the relationship can be applied to regions where historical meteorological or yield data are incomplete, or where correlations between rainfall and observed grain yield are inadequate for hedging purposes (even if significant correlation exists).

The basis risk resulting from the spatial heterogeneity of the precipitation-based index requires further analysis, since solutions exist to improve the spatial representation of the index through extrapolation techniques, spatial mapping through teledetection, or by using *ad hoc* indices created from the aggregation of multiple weather variables (VEDENOV and BARNETT, 2004).

The application of weather derivatives is also subject to risks unrelated to climate or agriculture, including the default of financial institutions or the interruption of the weather market itself, due to lack of liquidity. Such lack of liquidity may preclude financial institutions from selling contracts, with the possibility that a few market protagonists may generate a non-competitive situation, eroding market transparency (SKEES, 1999, 2002; HULL, 2002; RICHARDS ET AL., 2004; JEWSON and BRIX, 2005). Recent developments showed that opportunities for trading weather derivatives are growing beyond the traditional industrial sectors that were dominated during the early 1990s by the energy industry (JEWSON and BRIX 2005), and new participants from construction, entertainment, banking (to cover the loans exposed to weather risk), and leisure have recently entered the market.

Integrated economic studies at farm level and not limited to maize production may show further opportunities for the application of risk transfer based on capital markets to the benefit of both the society optimizing its investments (SKEES, 1999, 2002; MIRANDA and GLAUBER, 1997) and the rural sector that is facing fundamental socio-economic and technical adaptations. Risk transfer is one strategy to increase the probability that the agricultural production chain can be secured and to safeguard the production of real, tangible agricultural commodities that can drop or rise in quantity and quality due to a multitude of reasons, but cannot be replaced solely by monetary values. In the big picture of hedging against weather risks, however, one has to consider that the risk is not eliminated or reduced, but is transferred to an organisation that can better manage it.

Application of weather derivatives may be influenced by the availability of seasonal weather forecasts. Their usefulness has been assessed in Europe for winter crop management (CANTELAUBE and TERRES, 2005), but specific studies focusing on forecasting seasonal precipitation dynamics are still scarce. In areas where seasonal weather forecasting represents a valid support to both crop management and to financial decisions (STONE and MEINKE, 2005), pricing corrections could be considered (JEWSON and BRIX, 2005). Projections of adverse weather and unsuitable soil conditions during the time of sowing can lead the farmer to change plans, and in extreme situations can even force him to switch to an alternative crop, with the consequence that hedging would be obsolete. Mechanisms for redeeming the contingent claim can be included in the specifications, but then it is necessary to reconsider weather and seasonal forecasting to recalculate the conditional expectation of premiums (AGARWAL, 2002). These last issues were not considered here because solutions are specific to regions, countries, and industries, where the strong territorial presence of insurance and government services will inspire more sophisticated contracts including redemption clauses, whereas applications in remote areas will encourage simplicity in contracts (SKEES ET AL., 2001).

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