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Weather Risk Management in Agriculture Using Weather Derivatives

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Abstract. The purpose of this paper is to examine weather risk management by application of weather derivatives in agriculture and evaluate the hedging efficiency. Agriculture is a sector highly sensitive to meteorological elements that affect the yield of many crops. The underlying weather indices depending on temperature, rainfall and wind speed are analysed. Pricing follows the index modelling method using the Burn analysis valuation for fair premium calculation. The proposal of hedging strategies against excess rainfall in the crop cycle using weather options for Kosice region in the east of Slovakia is investigated and discussed. Results show that the weather derivatives application in weather risk management reduced the yield volatility in agriculture.

Keywords: weather risk management, weather option, rainfall index, burn analysis, hedging efficiency.
JEL codes: G130.

HIGHLIGHTS

- The risk of unfavourable price movements impacts on the yields from agriculture business.
- Temperature, rainfall, and wind speed data serve to model the underlying weather indices and option pricing.
- Weather hedging strategies against excess rainfall in the crop cycle using call and put options are the new tools in weather risk management in agriculture.
- Adoption of the weather derivatives can reduce the yield volatility of producers.

1. INTRODUCTION

Weather has had a growing impact on the economy in the last decades. Štulec (2017) states that approximately four-fifths of the world economy is directly or indirectly exposed to the weather.

Weather impact can be either catastrophic or non-catastrophic. Catastrophic weather includes low-probability events that cause huge financial damage, such as floods, hurricanes, and tornadoes. For example, the paper by Falco *et al.* (2014) studies the role of financial insurance in farmers' hedging against the implications of climate change. Traditional insurance can be used to avoid high losses coming from catastrophic events, but it does not provide an adequate solution to mitigate financial losses caused by non-catastrophic weather conditions (Cyr *et al.*, 2010). Non-catastrophic weather refers to small deviations from normal weather with a high probability of occurrence (Brockett *et al.*, 2005; Bartkowiak, 2009). With the introduction of weather derivatives, subjects can now hedge their exposure to non-catastrophic weather events (Stulec *et al.*, 2016). Leggio (2007) states that companies use weather derivatives to stimulate sales and diversify investment portfolios.

Weather derivatives are contracts with the payoff depending on weather (Alexandridis and Zapranis, 2013a). The underlying weather asset is the weather index since weather is not a physical good. The weather market is incomplete in the sense that the underlying weather indices are not tradable. Most studies (Davis, 2001; Alaton *et al.*, 2002; Cao, Wei, 2004; Richards *et al.*, 2004; Benth and Benth, 2007; Zapranis, Alexandridis, 2009; Zapranis, Alexandridis, 2011) have investigated the weather derivatives including pricing. Alternative methods for pricing options when the underlying security volatility is stochastic are examined by Heston (1993), Alaton *et al.*, (2002), Brody *et al.* (2002), Benth (2003), Benth and Benth (2005), Turvey *et al.* (2006), Benth *et al.* (2007), Benth (2011), Benth and Benth (2011), Swishchuk, and Cui (2013).

The use of weather derivatives has proven to be effective in many industries (Yang, 2011). Agriculture depends more on the weather and climate than many other sectors. Business uncertainties and the environmental impact of farming justify the significant role that the public sector plays for farmers. The EU common agricultural policy, known as the CAP, supports the farming sector in all EU countries. The aims of the CAP are to help farmers and increase food security. The scientific literature (Schwalbert *et al.*, 2020; Chavas *et al.*, 2019; Trnka *et al.*, 2016; Cantelaube, Terres, 2005) has examined how crop yield is impacted by weather. Understanding of weather impacts on crop yield is an important aspect of food security. The relationship between weather and crop yields is very complex because weather affects both the quantity and quality of the crop. Crop cultivation is often influenced by several meteorological elements that are interrelated, for example, temperature, sunlight, humidity, rain, wind, snow, etc. (Stulec *et al.*, 2016). Weather extremes occur more often, having major consequences for plant cultivation and also livestock farming. Weather derivatives as non-catastrophic weather risk management solution for agricultural business are investigated in various studies (Chen *et al.*, 2006; Deng *et al.*, 2007; Taušer, Čajka, 2014). For example, Vedenov and Barnett (2004) studied the weather derivatives in corn, soybean, and cotton production in two regions of the United States. Spaulding *et al.* (2003) studied the efficiency of put option in hedging of corn and wheat production in Romania. Weather put option in corn production in Switzerland was investigated by Torriani *et al.* (2008). Markovic and Jovanovic (2011) examined the effectiveness of put option hedging in winter barley production in Germany. Zara (2010) concluded that hedging using the Strangle strategy results in a 22.06% lower volatility of the economic value of grape production compared to the economic value of grape production without hedging. Raucci *et al.* (2019) designed a weather derivative contract and evaluated hedging efficiency in the Brazilian soybean market. Their findings showed that the adoption of weather-based derivatives reduces the income volatility around 30%. Turvey (2001) also examined the economics and pricing of weather derivatives taking into account the Ontario market and rain and heat-based call and put options. In Bobriková (2016), we focused on weather derivatives and their application in agriculture. We presented options with the payoffs depending on temperature index HDD suitable for farmers affected by extremely cold or hot winter. Hedging strategies against unfavourable temperature conditions were created and an economic analysis was performed. Weather risk is of particularly great importance for the energy industry. Papers by Müller and Grandi (2000), Cui and Swishchuk (2015), and Matsumoto and Yamada (2021) analyzed various types of weather-related risks in the energy market.

Based on the above papers we can conclude that weather derivatives are considered to be effective if their application leads to lower volatility in the economic value of the output. There is no generally accepted criterion for measuring the effectiveness of weather derivatives. Most authors Ender and Zhang (2015), Zhou *et al.* (2018), and Raucci *et al.* (2019) analyze the variance and standard deviation to assess their effectiveness in reducing yield volatility.

In this paper, we study the role of weather derivatives in hedging against the impact of non-catastrophic weather conditions in agriculture. We analyse several weather variables, i.e., temperature, precipitation, and wind speed. Based on the partial findings, we calculate the Rainfall index and the premiums of call and put options with the payoff function depending on the rainfall. The Burn analysis is used in pricing of call and put options. The study of the role of weather derivatives in hedging is conducted in the Košice region of Slovakia. We also design hedging strategies and their substrategies that can stabilize the economic value of the agricultural production which is affected by the precipitation. Our findings can be useful to farmers who are exposed to the risk of an unfavourable increase in precipitation and its impact on their yields. In addition, the paper presents hedging effectiveness of the proposed strategies. Hedging strategies for farmers in Slovakia can support public policy aimed to increase global food security by mitigating the effects of catastrophic events. The issue of food security addressed from various perspectives including climate change is provided in the book by De Castro *et al.* (2012).

2. RESEARCH METHODOLOGY

The agricultural sector has high exposure to weather risks. For this reason, farmers are one of the main potential users of weather derivatives. Our aim is to design weather derivatives for risk management in agriculture and to evaluate the hedging efficiency against adverse weather conditions. Our research methodology consists of 3 steps. The first step is to find the best underlying weather index for agriculture using correlation analysis and to price the weather derivatives using the Burn analysis. In the second step, the weather derivatives are proposed and compared. Finally, the hedging efficiency of weather option strategies is examined and discussed.

The underlying index is one of the most important parameters of weather derivatives. Popular indices are temperature, wind speed, wind power, rainfall, hurricane, and humidity. Temperature related weather derivatives are the most frequent type on the market. Three indices are determined and used by temperature derivatives: Heating Degree Days (HDD), Cooling Degree Days (CDD) and Cumulative Average Temperature (CAT). These indices are the most favoured by the energy companies (Bemš and Aydin, 2021). Unlike the energy sector, where there is a presumption of a clear relationship between energy consumption and temperature, agriculture assumes a similar presumption of a relationship between production and some weather variables. Therefore, we decided to examine the relationship between several weather indices based on different weather factors and yields from agriculture products in a selected region. Previous studies (Turvey, 2001; Hess *et al.*, 2002; Musshof *et al.*, 2011; Alexandridis and Zapranis, 2013b; Ender and Zhang, 2015; Bobriková, 2016; Raucci *et al.*, 2019), have focussed on weather risk management using weather derivatives in agriculture. Taking into account their findings we adopt the following weather indices:

- temperature indices – CAT and CDD,
- rainfall index RAINFALL,
- wind speed index CAWS.

CAT (Alexandridis, 2012) is defined as:

$$CAT(t) = \sum_{i=1}^{t} T_i \quad (1)$$

- $CAT(t)$ is the cumulative average temperature for the period t,
- t is number of days.

According to Alaton (2002), the degree day index CDD is:

$$C_t = \sum_{i=1}^{t} CDD_i \quad (2)$$

- C_t is the cumulative for the period t,
- t is number of days,

where

$$CDD_i = max\{T_i - 18 \, ; 0\} \quad (3)$$

- CDD_i is the Cooling Degree Days for the day i.

Rainfall index is expressed by the formula (Cramer, 2019):

$$Rainfall_t = \sum_{i=1}^{t} r_i \quad (4)$$

- $Rainfall_t$ is the rainfall index,
- r_i is the amount of precipitation for the day i.

CAWS is the sum of daily average wind speeds over a period of time and is given by Alexandridis (2012) as:

$$CAWS_t = \sum_{i=1}^{t} DAWS_i \quad (5)$$

- $CAWS_t$ is the wind speed index for the period t,
- $DAWS_i$ average wind speed for the day i.

If farmers want to ensure their yields by hedging with options, they must first pay the price in the form of an option premium. Since weather options are not traded on the market, their price must be determined

(Musshof *et al.*, 2011). Three parameters are needed to calculate the price – the strike value, the spot value of the index and the tick size. The spot value of the index is calculated for each year on the basis of historical data. The tick size is set at 1 Euro. We determined the strike values on the basis of the average and standard deviation of the annual Rainfall index:

$$K_1 = \frac{1}{N}\sum_{i=1}^{N} Rainfall_i - \frac{\sigma}{2} \tag{6}$$

$$K_2 = \frac{1}{N}\sum_{i=1}^{N} Rainfall_i \tag{7}$$

$$K_3 = \frac{1}{N}\sum_{i=1}^{N} Rainfall_i + \frac{\sigma}{2} \tag{8}$$

- k_1, k_2, k_3 are strike prices,
- σ is standard deviation of the underlying index during the period,
- $Rainfall_i$ is value of the underlying index in year i,
- N is number of years.

After determining the strike prices, we apply the pricing method Burn analysis. This method calculates the expected payoff of weather option as the average of the payoffs in the past during the period (Jewson, Brix, 2005; Benth and Benth, 2007). The expected payoff is defined by the equation:

$$Expected\ payoff = \frac{1}{n}\sum_{i=1}^{n} p_i \tag{9}$$

with payoff p_i in the year i and the call and put option premiums:

$$p_{ic} = max\{R_i - K;0\} * tick\ size\ for\ call\ option \tag{10}$$

$$p_{ip} = max\{K - R_i;0\} * tick\ size\ for\ put\ option \tag{11}$$

The symbol R_i refers to the rainfall index value in the year *i*. The symbol K is the strike index. The price of options can be calculated as a so-called fair premium using the Burn analysis. The term fair premium means a price at which the expected profit from an option for both parties is exactly zero. If risk premiums for the seller or buyer or transaction costs are not taken into account, the option price can simply be calculated as the expected payoff of the option. Since the option premium is paid at the time of the contract conlusion, the amounts expressed by (10) and (11) is discounted at the annual risk-free interest rate *r*. Based on the above, the price of options can be expressed as:

$$option\ premium = e^{-rT} * \frac{1}{n}\sum_{i=1}^{n} p_i \tag{12}$$

- r is risk-free interest rate,
- T is maturity period of an option.

The purpose of the proposed weather option hedging strategies is to hedge farmers' yields in the selected region against adverse weather condition during the year. We specify the contract maturity of 1 year. The proposed weather derivatives are options on the underlying weather index.

Generally, an option strategy involves the simultaneous combination of two or more option positions (Long Call, Short Call, Long Put, and Short Put). A call option gives the holder (buyer)/writer (seller) the right to buy/the obligation to sell an underlying weather index at a fixed strike price. A put option gives the buyer/seller the right to buy/sell the obligation to buy an underlying weather index at a fixed strike price. The buyer of an option has to pay an initial sum of money called the premium to the seller of the contract. Options may be combined, by means of which new forms and attractive investment opportunities are created. Option hedging strategies are presented in papers by Rusnáková (2015), Timková (2018) and Bobriková (2021).

Option hedging strategies designed and discussed in this paper and the characteristics of these strategies are listed in Table 1.

The selection of a suitable option hedging strategy is a systematic process based on the farmer's attitude to risk (high/neutral/low risk aversion) and expected payoff. Each of the strategies has strengths and weaknesses, which will be discussed in the results.

Hedge effectiveness of strategies is also investigated. Weather derivatives are considered effective if their application leads to reducing yield volatility, i.e., decreasing the uncertainty of future cashflows. We use the most common measure of volatility, i.e., the variation coef-

Tab. 1. Option strategies and characteristics.

	Volatility	Risk
Long Call	bulish	low
Long Straddle	neutral	low
Long Strangle	neutral	low

ficient and standard deviation. Firstly, we express the profits and losses in thousands of EUR from the hedging option strategies over the years 2010-2019. Subsequently, we create scenarios of yield development by adding these profits and losses to the annual yields of crops.

3. RESULTS

3.1. Data

The study was conducted in the Košice region of Slovakia. This region was chosen due to its high agricultural production. Kosice region with an area of 6 754.3 km^2 is located in the southeast of the Slovak Republic and occupies 13.8% of its territory. Agricultural land occupies 333 000 ha, which is almost half regional area; more than three-fifths of it is arable land and one third is permanent grassland and meadow (Statistical Office of the Slovak Republic, c2022).

Data were drawn from the European Climate Assessment & Dataset (ECA&D) database and the database of the Statistical Office of the Slovak Republic (DATAcube). This study analyses the impact of weather variables on crop yields using weather data from the Košice-airport meteorological station over the period 1980-2020 and annual yields from agricultural products in Košice region over the period 2010-2019. The weather dataset set consists of historical daily minimum and maximum temperature, precipitation, and wind speed.

3.2. Underlying weather indices and pricing of weather options

We analysed the development of the indices CAT, CDD, RAINFALL and CAWS. Basic statistical characteristics are in Table 2.

We performed a correlation analysis between selected weather indices and yields from agricultural products in the Košice region for the period 2010-2019. The correlation matrix is presented in Table 3. The results show that the Rainfall index has the highest correlation with yields. The correlation coefficient of -0.47 means a slightly negative correlation. The second highest correlation is the CAWS index with a correlation coefficient of 0.42, which indicates a slightly positive correlation. The CAT and CDD indices show only a weak correlation with the yields.

Based on the above analysis, we can say that the most suitable underlying index for the proposed weather derivatives for farmers in the Košice region is the Rainfall index. Therefore, we will focus on the valuation of weather derivatives based on the underlying Rainfall index. We use the Burn method in pricing. Rainfall index development from 01/01/1980 to 31/12/2020 is shown in Figure 1.

Tab. 2. Basis statistical characteristics of indices.

	CAT	CDD	RAINFALL	CAWS
Average	3843	2132	639	1153
Median	3742	2104	583	1162
Standard deviation	234	139	140	69
Dispersion	54822	19196	19633	4730
Margin	688	505	447	224
Minimum	3508	1960	512	1029
Maximum	4196	2466	959	1253
Variation coefficient	0.06	0.06	0.22	0.06

Tab. 3. Correlation matrix of weather indices and yields in agriculture.

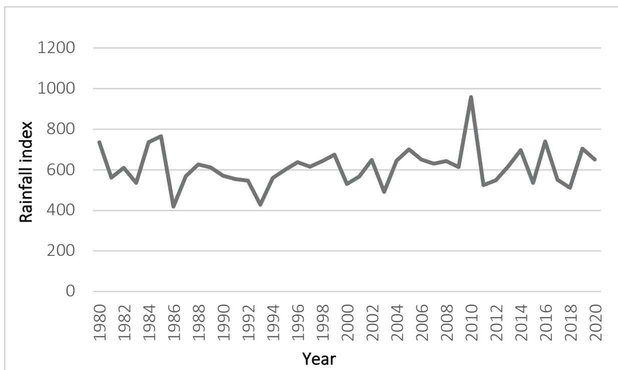
	CAT	GDD	RAINFALL	CAWS	Yields
CAT	1				
GDD	0.69	1			
Rainfall	-0.28	-0.54	1		
CAWS	0.08	0.38	-0.26	1	
Yields	0.24	0.28	-0.47	0.42	1

The payouts and average payouts of the proposed call and put options during the analysed period can be provided on request. We calculated premiums of call and put oprions with the time to maturity 1 year. The premiums are shown in Table 4.

3.3. Design of hedging strategies using weather options

In agriculture, extreme weather conditions (e.g., both too little and too much rainfall) cause falls in yield.

Fig. 1. Graph of the Rainfall index development.



Tab. 4. Call and put option premiums.

Premium of Call option	Strike price based on Rainfall index	Premium of Put option
62.90	565.3	14.90
34.99	613.6	34.99
18.17	662.0	66.17

Tab. 5. Hedged scenarios by Long Call strategy.

Rainfall index range	Unhedged index value	Payoff from strategy	Hedged index value
R_T<K	-R_T	-c_L	-R_T -c_L
R_T≥K	-R_T	R_T-K- c_L	-K-c_L

Tab. 6. Hedged scenarios by Long Call strategy.

Rainfall index range	Unhedged index value	Payoff from strategy	Hedged index value
R_T<565.3	-R_T	-62.9	-R_T -62.9
R_T≥565,3	-R_T	R_T-565.3 -62.9	-628.2

Thus, the combination of a put and a call option based on the same underlying index can be appropriate (Berg *et al.*, 2006). Our aim is to design weather option hedging strategies using call and put options on the underlying Rainfall index against adverse weather conditions, specifically against excessive rainfall during the year.

The first strategy which can be used in the price risk management against excessive rainfall is Long Call strategy. We assume that the actual Rainfall index value is R_0. The call option on the rainfall index will attract a farmer whose profits are affected by the high rainfall index values in the future R_T. Long Call option on Rainfall index is the right to buy the rainfall index value for a fixed strike price K at maturity time T. The future payoff for every scenario is given in Table 5. Two variants of the scenario can occur at the maturity of an option. If the Rainfall index value at maturity date T is below the strike price K, then the farmer will lose the option premium c_L which is the cost of weather risk management. If the Rainfall index value at maturity date is above the strike price, then the farmer will obtain the payoff of (R_T -K-c_B).

Strategy 1: Long Call with the strike index value = 565.3 a premium = 62.9. The payoffs from this strategy and hedged index values are listed in Table 6.

Table 7 illustrates hedged index value and profit/loss from hedging strategy as the difference between the hedged rainfall index value and unhedged rainfall index value at maturity date T. If the difference is positive (more than 0), the hedged position is better than the unhedged position.

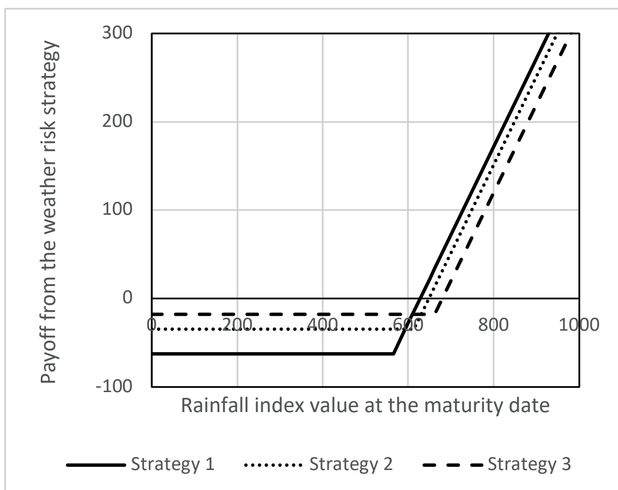
Tab. 7. Hedged rainfall index value by Long Call strategy.

Rainfall index range	Hedged index value	Profit of hedging		Loss of hedging	
		Min	Max	Min	Max
R_T<565.3	-R_T-62.9	–	–	62.9	62.9
565.3≤R_T≥628.2	-628.2	–	–	0	62.9
628.2≤R_T	-628.2	0	∞	–	–

We created Strategy 2: Long Call with the strike index value K = 613.6 a premium = 34.99 € and Strategy 3: Long Call with the strike index value K = 662 a premium = 18.17 €. The comparison of payoffs from Strategies 1, 2 and 3 at various development of Rainfall index value at the maturity date is shown in Figure 2.

Using options with various strike index value, the hedging profit sensitivity could be examined. For an option buyer, the premium represents the maximum cost that can be lost. If the strike index value is higher, lower costs are needed for the buying of an option and therefore the profit from the strategy is lower. The profit is unlimited. The loss is limited by the option premium. It can be seen, but also be calculated exactly using payoffs from strategies that the weather risk strategy 1 ensures the highest profit if the rainfall index value at the maturity date is higher than 593.21. The cost of this benefit is the highest option premium. This hedging variant is available to the farmer with a higher degree

Fig. 2. Comparison of payoffs from the weather risk strategy Long Call.



Tab. 8. Hedged scenarios by Long Straddle strategy.

Raifall index range	Unhedged index value	Payoff from strategy	Hedged index value
$R_T<K$	$-R_T$	$-R_T+K-c_L-p_L$	$-2R_T-K-c_L-p_L$
$R_T\geq K$	$-R_T$	$R_T-K-c_L-p_L$	$-K-c_L-p_L$

Tab. 9. Long Straddle strategies.

	Strike price	Premium of Long Put	Premium of Long Call
Strategy 4	565.3	14.9	6.9
Strategy 5	613.6	34.99	34.99
Strategy 6	662	66.17	18.17

Tab. 10. Hedged scenarios by Long Strangle strategy.

Rainfall index range	Unhedged index value	Payoff from strategy	Hedged index value
$R_T<K_1$	$-R_T$	$-R_T+K_1-p_L-c_L$	$-2R_T+K_1-p_L-c_L$
$K_1< R_T\leq K_2$	$-R_T$	$-p_L-c_L$	$-R_T-p_L-c_L$
$R_T\geq K_2$	$-R_T$	$R_T-K_2-p_L-c_L$	$-K_2-p_L-c_L$

Tab. 11. Long Strangle strategies.

	Strike price of Long Put	Premium of Long Put	Strike price of Long Call	Premium of Long Call
Strategy 7	565.3	14.9	613.6	34.99
Strategy 8	613.6	34.99	662	18.17
Strategy 9	565.3	14.9	662	18.17

of risk aversion. A low-risk-aversion farmer will prefer the hedging strategy 3. If the rainfall index value at the maturity date is lower than 593.21 the loss of hedging strategy 3 is the lowest. The weather risk strategy 2 is the most suitable hedging strategy for the farmer with a neutral risk aversion.

Long Straddle strategy can also be a weather risk management tool. It is formed by Long put option position with a strike price K and option premium p_L and Long call option with the same strike price K and option premium c_L. The payoff for every scenario is indicated in Table 8.

3 substrategies of Long Straddle strategy are given in Table 9 and their comparison is shown in Figure 3.

We can deduce following conclusions. The Long Straddle Strategy is the most expensive of the analysed hedging strategies. It can be seen, but also calculated, that the Long Straddle strategy 4 ensures the highest payoff or the lowest loss if the rainfall index value at the maturity date is higher than 610.38. On the other hand, strategy 4 has the most loss if the rainfall index value at the maturity date is lower than 593.36. It is suitable for a farmer who expects lots of rainfall.

Long Straddle strategy 6 ensures lower payoff in the case of high Rainfall index values but higher payoff at low Rainfall index value. Strategy 5 is for the neutral risk aversion farmers.

The Long Strangle option strategy, like the Long Straddle, provides the opportunity to hedge against high and low values. It is created by buying n call options with a lower strike price K_1 and buying n put options on the same underlying index with a higher strike price K_2. This strategy is suitable for farmers whose yields are negatively affected by high or low underlying index values. The payoff of Long Strangle strategy is given in Table 10.

Parameters of proposed Long Strangle substrategies are in the Table 11.

The comparison of option strategies 7, 8 and 9 is shown in Figure 4. We can state that:

- Strategies 7 and 9 have different strike index values of Long Call option. The higher the strike price of Long Call, the lower the payoff in the case of index growth, i.e., more precipitation. On the other hand, the higher the strike price of Long Call, the higher the payoff in the case of index fall.
- Strategies 8 and 9 have different strike index values of Long Put option. The lower the strike price of Long Put, the higher the payoff in the case of index growth. The lower the strike price of Long Put, the lower the payoff in the case of index fall.

Fig. 3. Comparison of payoffs from the weather risk strategy Long Straddle.

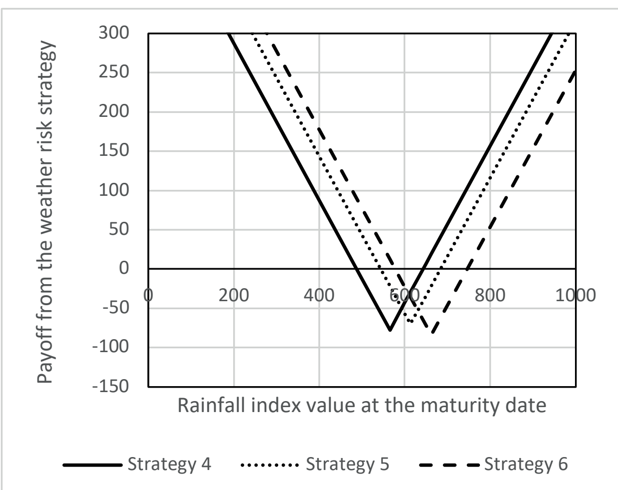
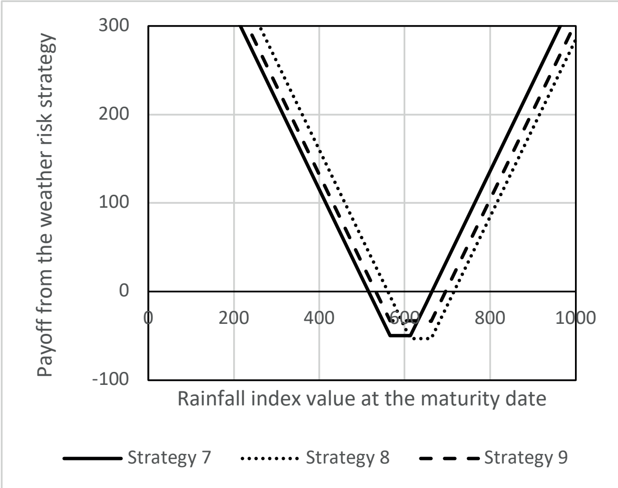


Fig. 4. Comparison of payoffs from the weather risk strategy Long Strangle.



- Strategy 7 ensures the highest profit compared to other strategies in the case of high values of the Rainfall index (more than 630.64), but on the other hand, the lowest profit in the case of low values of the Rainfall index. Strategy 8 is the best if the index value is lower than 593.51 at the maturity date. Strategy 8 is appropriate for farmers who want to hedge against too little precipitation. Strategy 9 generates medium rainfall index values. Therefore, it is the potential strategy for both too low and too high rainfall expectations.

3.4. Hedging effectiveness

Using ex post analysis, we examine the hedging effectiveness. Is it possible with the application of the proposed hedging strategies to reduce the volatility of farmers' yields? We measured the hedging efficiency similar to Spaulding *et al.* (2003) and Zara (2010) using the variation coefficient.

We calculate the profits and losses in thousands of EUR from the option hedging strategies within the years 2010-2019. The hedge scenarious represent the development of yields with hedging strategies application. The profits/losses from the hedging strategy are shown in Table 12 and hedged yields are presented in Table 13.

By comparing the volatility of unhedged yields with that of hedged yields with application of strategies S1-S9, we found that the volatility of yields measured by variation coefficient decreased (Table 14). Based on the analysis, the most effective strategy is strategy 4. The findings show that application of this strategy results in lower volatility of the yield by 15.66% compared to the value of the yields without the weather option strategy application. Strategy 6, which reduced yield volatility by 9.46%, reaches the worst results. Figure 5 shows the development of yields with (gray line) and without (black line) weather application for strategy 4.

Based on the hedge effectiveness analysis, it can be conluded that application of the proposed hedging strategies reduced the volatility of yields by 9.46 to 15.66%. Our findings confirmed the hypothesis that the application of weather option strategies reduced the farmers' yield volatility in agriculture. Results suggest that weather derivatives can be considered as appropriate tools to hedge against adverse weather conditions.

4. CONCLUSION

Weather derivatives are the new non-catastrophic weather risk management tool. Although they were originally developed in the United States for the energy industry, their application is now possible in many other

Tab. 12. Profit/losses in thous. EUR from hedging strategies S1-S9.

	S1	S2	S3	S4	S5	S6	S7	S8	S9
2010	49 605	46 547	41 810	47 372	41 297	31 883	44 312	36 561	39 575
2011	-9 435	-5 249	-2 726	-5 489	2 926	8 032	-1 304	5 451	1 219
2012	-9 435	-5 249	-2 726	-9 209	-793	4 313	-5 024	1 731	-2 500
2013	-1 785	-4 843	-2 726	-4 018	-10 093	-5 798	-7 078	-7 974	4 961
2014	10 719	7 660	2 923	8 485	2 410	-7 004	5 425	-2 325	688
2015	-9 435	-5 249	-2 726	-7 352	1 063	6 169	-3 167	3 588	-644
2016	16 744	13 685	8 948	14 510	8 435	-979	11 450	3 700	6 713
2017	-9 435	-5 249	-2 726	-9 464	-1 049	4 057	-5 279	1 476	-2 756
2018	-9 435	-5 249	-2 726	-3 643	4 772	9 878	542	7 296	3 065
2019	11 325	8 266	3 529	9 091	3 016	-6 398	6 031	-1 719	1 294

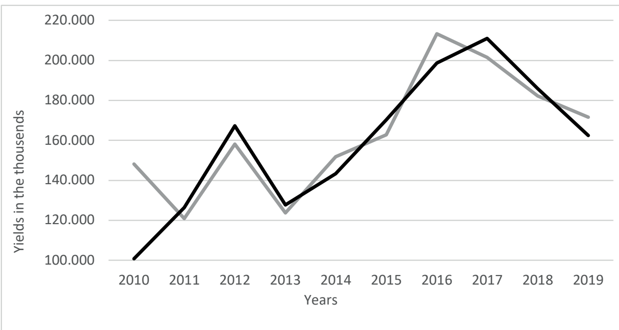
Tab. 13. Unhedged yields and hedged yields by hedging strategies 1-9.

	Yields (Y)	Y+ S1	Y+ S2	Y+ S3	Y+ S4	Y+ S5	Y+ S6	Y+ S7	Y+ S8	Y+ S9
2010	100 811	150 416	147 357	142 620	148 182	142 107	132 693	145 122	137 372	140 385
2011	126 417	116 982	121 169	123 692	120 929	129 344	134 450	125 114	131 868	127 637
2012	167 276	157 841	162 028	164 551	158 068	166 483	171 589	162 253	169 007	164 776
2013	127 677	125 892	122 833	124 951	123 658	117 583	121 879	120 598	119 703	122 716
2014	143 270	153 989	150 930	146 193	151 755	145 680	136 266	148 695	140 945	143 958
2015	170 228	160 793	164 979	167 502	162 876	171 291	176 397	167 061	173 815	169 584
2016	198 739	215 483	212 425	207 688	213 250	207 175	197 761	210 190	202 439	205 453
2017	210 921	201 486	205 673	208 196	201 458	209 873	214 979	205 643	212 397	208 166
2018	185 910	176 475	180 662	183 185	182 267	190 682	195 788	186 452	193 206	188 975
2019	162 466	173 791	170 733	165 996	171 558	165 483	156 069	168 498	160 747	163 761

Tab. 14. Decrease of the variation coefficient by application of hedging strategies in %.

	S1	S2	S3	S4	S5	S6	S7	S8	S9
Variation coefficient (in %)	*-14.78*	*-14.62*	*-15.53*	*-15.66*	*-12.37*	*-9.46*	*-14.64*	*-11.50*	*-19.12*

Fig. 5. Graph of the yield development with and without weather application: the case of hedging strategy 4 for the period 2010-2019.



sectors, including agriculture. Agriculture and the global food supply are susceptible to the impacts of climate change. Slovakian agriculture and food supply are no exception to this. The use of weather derivatives as risk management tools in Slovak agribusiness is non-existent. Thus, this paper has contributed to filling a gap in the literature with the aim of improving the weather risk management activities of producers. The methodology of this research can also be helpful for weather derivative hedging in other regions.

In the theoretical part of the paper, we focused on introduction to the weather derivatives. We characterized the main parameters, which include: type of contract, contract period, underlying index etc. The main part provided the analysis of hedging using weather derivatives in agriculture and the design of weather derivatives for hedging of farmers in the Košice region. We used a correlation analysis, in which we examined the relationship between individual weather indices and farmers' yields. We found that the most appropriate underlying index is the Rainfall index. Call and put options were evaluated based on the underlying Rainfall index using the Burn method.

Subsequently, using these options, we proposed 9 strategies, which we analyzed and compared. Based on the results of the analysis and comparison we formulated recommendations for farmers in terms of their use of hedging in agriculture in the Košice region. Based on a review of expert studies, we performed an ex-post analysis of effectiveness of weather hedging in agriculture, which was measured by the relative reduction in yield volatility. By comparing the volatility of hedged yield development with the unhedged yield, we found that producers were able to reduce the climate risk with a significant fall in yield variation using Rainfall index hedging option strategies. The results show that the proposed strategies are effective in weather risk management in agriculture. The most effective strategy is strategy 4. Adoption of the weather derivatives reduced the yield volatility of producers (expressed by the variation coefficient) by up to 15.66%. We can confirm that the weather derivatives offer unique risk management instruments for agricultural producers.

Further research can provide the hedging efficiency of mixed-based weather derivatives that are based on several weather variables, e.g., temperature and rainfall. Moreover, an important issue is to investigate the potential benefits and limitations of weather derivatives for particular crops and areas. Finally, other climate models can suggest a double seasonal analysis for meteorological variables.

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