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Development of weather derivatives: evidence from the Brazilian soybean market

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Abstract. The purpose of this study is to design a weather derivative contract and evaluate the hedging efficiency into the Brazilian soybean market against lack of rainfall in the crop cycle. We adopt European put options with two different types of underlying rainfall index (equal-weighted index and growth-weighted index), using a dataset of daily precipitation and annual production for six areas located in the south of Brazil. Pricing follows the index modeling method, using the estimated payoff distribution for fair premium calculation. The contract premium varied from 10% to 15% of revenue per hectare. Results show that the adoption of the weather-based derivatives reduced the producers' income volatility substantially (around 30%).

Keywords: weather derivative, rainfall derivative, weather risk, soybeans.
JEL codes: G22, G32, Q02, Q14.

1. INTRODUCTION

Over the last decades, new risk management tools have been developed in order to help different types of businesses reduce income variability. The weather derivative is an example. Introduced in the late 1990s in the U.S., temperature derivative contracts have been used by the energy industry to protect against adverse weather conditions. Recently, weather risks have also been managed using derivatives based on rainfall, snowfall, wind, frost, hurricane, etc., attracting the attention of other industries such as agriculture, entertainment, tourism, construction, and retail (Jewson, Brix, 2005).

Focusing on agriculture, rainfall derivatives play a similar role to that performed by crop insurances. However, the advantage of these contracts over conventional crop insurances is their payoff structure, which depends exclusively on the occurrence of a specific weather event measured by an available index. Despite the correlation of weather events with yield variations, the payoff of the weather risk product is independent of crop yields, i.e. there is no loss adjustment at the farm-level. Consequently, moral hazard and adverse selection problems, which arise from information asymmetry and

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are inherent in crop insurances, are eliminated (Turvey, 2001; Vedenov, Barnett, 2004; World Bank, 2005). Nevertheless, even with these advantages, weather-based derivatives have low usage (Khan *et. al.*, 2013; Sibiko *et. al.* 2018). Leblois and Quirion (2013) point to some barriers that restrict the adoption of these contracts. Among several factors, one key element is the misunderstanding about the weather insurance design, highlighting issues related to farmers' educational background. In addition, basis risk has been pointed as a relevant concern for adopting weather derivatives[1] (Woodard, Garcia, 2008a). Under specific circumstances, weather basis risk could be significantly high, reducing hedging effectiveness.

Previous studies have investigated the use of weather derivatives in agriculture (Khan *et. al.*, 2013; Pelka, Musshoff, 2013; Musshoff *et. al.*, 2011; Zhou *et. al.*, 2018), including basis risk analysis and hedging effectiveness (Woodard, Garcia, 2008a; Torriani *et. al.*, 2008; Möllmann *et. al.*, 2019). However, little attention has been paid to the use of weather derivatives in agricultural activity in emerging markets, which play an important role in world commodity supply. Taking into account the current climate change scenario and considering the limited scope of crop insurances in these economies (in general, strongly dependent on government subsidies), the weather-related insurance products could offer new ways to manage risk in agricultural markets.

Therefore, the objective of this study is to design a rainfall put-option and evaluate the hedging efficiency in the soybean market in the south of Brazil. Brazil was chosen for its dynamism and importance in the international market, being responsible for around 1/3 of the worldwide soybean production in 2010s (USDA, 2019). In addition, the focus on the south of Brazil is particularly relevant since it is a traditional grain-producing region with an unstable weather. Furthermore, between 2010 and 2018, soybean crop responds around 40 to 50% of financial volume of agricultural insurances in Brazil, as well as south region responds around 25% of total insured areas in the country, reinforcing the importance of the analysis for this crop and region (MAPA, 2018).

Overall, our main hypothesis is that the use of this contract can reduce farmer income volatility, offering new risk management instruments for agricultural production. Using European put options and a dataset of daily precipitation and annual production from 1992 to 2016, our findings confirmed the hypothesis. Results suggest that the adoption of rainfall put-option reduced the producers' income volatility by around 30%.

2. LITERATURE REVIEW

Several recent studies have investigated the use of weather-based derivatives. A number of factors have stimulated these studies, such as the current climate change scenario, the increasing availability of alternative crop insurance products, and the expansion of derivative markets in different countries.

Previous studies have investigated the factors influencing the adoption of weather derivatives, as well as uncovering the characteristics and the limits associated to the use of such contracts. Seth *et. al.* (2009), for example, evaluated the use of weather derivatives among small farmers in India. Their findings show that the producers would be willing to pay a maximum premium equal to 8.8% of the payout of the operation for these instruments. In addition, Leblois and Quirion (2013) analyzed different experiences of using weather derivatives in India, Ethiopia, and Malaui. Despite positive results in terms of the number of insured producers, the authors question the benefits of these experiences, given the high costs of the programs and the difficulty in measuring the direct effects of adopting weather derivatives. Further, Khan *et. al.* (2013) explored the climate risk strategies by Canadian wheat producers. The authors verified that the low adoption of weather-based derivatives by producers is a result of lack of knowledge about these instruments - 59% of those who did not use index-based insurance were not aware of this type of contract. In line with these studies, Sibiko *et. al.* (2018) provided interesting points into this topic, evaluating the use of weather index insurance (WII) by farmers located in Embu County, Kenya. The authors observed that, even with the implementation of WII initiatives since 2009, the adoption of these insurance contracts by farmers was lower than 10%. The lack of understanding of the WII and the price of the insurance were pointed as some of the problems that impacted the demand for these contracts.

Another group of studies focused on hedging effectiveness. Vedenov and Barnett (2004), for example, investigated the efficiency of weather derivatives as insurance instruments in producing areas of maize, cotton, and soybean in the United States. They concluded that the effectiveness of such instruments varies sub-

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[1] The basis risk arises from «the fact that the correlation between crop yield and the meteorological index cannot be perfect» (Leblois, Quirion, 2013, p.1). In general, this correlation is impacted by the spatial variability of the weather conditions considering meteorological station and hedged location. The nonlinear relationship between weather indexes and crop yield brings more complexity to this topic (Richards *et al.*, 2004). In addition, crop yield can be also impacted by biological factors (such as the occurrence of pests and diseases), which are not necessarily directly associated with weather events.

stantially across crops and regions. Berg *et. al.* (2006) focused the analysis on the potato market in Germany. The authors found that the hedge was less effective in situations of low correlation between the meteorological index (used in the derivative) and the crop yield. Further, Stoppa and Hess (2003) explored the adoption of rainfall derivatives by grain producers in Morocco. The use of a rainfall put option helped to protect producers' income losses caused by low rainfall. In addition, Zhou *et. al.* (2018) examined the effectiveness of rainfall index insurances on the crop yield risk, taking into account corn activity in Illinois, US. Findings suggested that the income variance decreased around 50% with the adoption of a weather-based insurance portfolio.

Turvey (2001) also contributed to this debate, comparing the efficiency of weather derivatives based on temperature and rainfall indexes for hay, maize, and soybean in Canada. Results suggested that such contracts helped to manage agricultural production risk, indicating that pricing must be location specific. Musshoff *et. al.* (2011) and Pelka and Musshoff (2013) conducted similar analysis, taking into account the German wheat market and temperature and rainfall-related option contracts. Their findings showed that the weather derivatives based on simple and mixed weather indices had high hedging effectiveness. Further, Shi and Jiang (2016) created a composite weather index insurance model, showing that such instruments consistently reduced yield risk in rice crops in China.

The aspects of weather basis risk have been also explored by a number of studies. Martin *et. al.* (2001), for example, evaluated the hedging effectiveness and basis risk of a flexible rainfall option in the U.S cotton market, showing that basis risk did not significantly undermine the benefits of these instruments. In addition, Woodard and Garcia (2008a) investigated the basis risk in the U.S. corn market, demonstrating that hedging effectiveness could increase by adopting basket weather derivatives from diverse locations. In a complementary study, Woodard and Garcia (2008b) provided new empirical evidence related to the use of weather derivatives, taking into account high levels of spatial aggregation. Results showed that the idiosyncratic risk decreases when production exposures were aggregated, suggesting a higher efficiency of weather derivatives for hedging yield exposures. These findings indicate the potential of weather derivatives in agriculture, particularly for reinsurers. In line with these studies, Torriani *et. al.* (2008) identified that, despite the occurrence of high basis risk, rainfall derivatives contributed to manage drought risks in grain maize production in Switzerland. Furthermore, Möllmann *et. al.* (2019) evaluated the adoption of weather derivatives using three remotely sensed vegetation indexes - vegetation condition index (VCI), temperature condition index (TCI) and vegetation health index (VHI). Focusing on the winter wheat production in Germany, the authors showed that the use of VHI- and VCI-based weather contracts reduced basis risk, improving hedging effectiveness.

Finally, weather-based derivatives were also examined in other markets. For instance, Chen *et. al.* (2006) and Deng *et. al.* (2007) evaluated the use of relative humidity and temperature derivatives to manage profit risk in dairy industry. Following the same idea, Cortina and Sánchez (2013), Cyr *et. al.* (2010), and Zara (2010) examined the use of temperature options in wine production in a context of climate changes. In addition, Štulec (2017) investigated the impact of the adoption of temperature options on beverage sales in Croatian food stores.

3. RESEARCH METHOD

The methodology used in this research is developed following three main steps. First, exploring the structure of the weather-based derivative. Second, developing a premium calculation. Third, analyzing hedge effectiveness. For a better understanding, the following sections provide a detailed discussion on these points.

3.1. Structure of the weather-based derivative

In order to reduce farmer income volatility, this study uses a European put option for the following reasons. First, considering the soybean activity in the south of Brazil, one of the most common risk events is based on droughts. Thus, put options can help to manage this type of risk, providing an indemnity if rainfall falls below a certain limit. Second, in order to enable a straightforward pricing method, along with considering the low chances of an early exercise of the put option, we adopted a European-style option. Consequently, this analysis is strictly focused on the risk of low precipitation, not assessing the risk of excessive rainfall events. In addition, the put option can only be exercised by hedgers (farmers) on the contract expiration date (at the end of the crop), not allowing early exercise. Under these conditions, three variables have to be defined to structure the weather-based derivative: underlying asset, strike price, and time to maturity. Based on such variables, the cost of rainfall insurance for the producer (known as an option premium) can be obtained.

According to Stoppa and Hess (2003) and Martin *et. al.* (2001), the weather hedging effectiveness increases as the correlation between the underlying asset of the contract (weather index) and the crop yield increases. Thus, the weather index must be able to explain most of the variability in crop yield. Consequently, the construction of the rainfall index (F_t) of the contract is weighted according to the stages of the crop – equation (1). Herein, the maximum correlation between the underlying rainfall index of the contract and the crop yield is achieved (Stoppa, Hess, 2003).

$$F_t = \sum_{i=1}^{12} \omega_i f_{it} \tag{1}$$

where ω_i is the weight given to each subperiod i of ten days, taking into account the Brazilian soybean crop cycle of 120 days (December to March), and f_{it} corresponds to the sum of daily rainfall for each subperiod i in the crop year t. The period was defined according to the 2017 Brazilian Agricultural Zoning.

The weights of the rainfall index are determined using an optimization problem – equation (2), which maximizes the correlation between the rainfall index and crop yield (Y).

$$max_{\omega_i} corr(F,Y) = \frac{\sum_t^T \left(F_t - \bar{F}\right)\left(Y_t - \bar{Y}\right)}{\left[\sum_t^T \left(F_t - F\right)^2\right]^{1/2} \left[\sum_t^T \left(Y_t - \bar{Y}\right)^2\right]^{1/2}} \tag{2}$$

$$\text{subject to } 0 \leq \omega_i, \ \forall i.$$

where t is the first year and T is the last year of the sample.

The study also uses an index of equal weights for each period of the plant's growth, giving the same importance to different cropping periods. In addition, to avoid inaccuracies from the calculation of the rainfall index, the study uses a limiting factor (equal to 75mm) of the daily capacity of water absorption by the soil (Fontana *et. al.*, 2001). Therefore, excessive rainfall cannot impact the result of the index.

After determining the underlying asset of the contract, the next step is to define the strike price of the option (K). This is given by the average rainfall index calculated between 1992 and 2016.

With respect to the payoff structure, the indemnity (I) is triggered when the index rainfall (F) falls below a specific strike (K) – equation (3). The payment is proportional to a previously defined maximum indemnity (θ). Summarizing, the greater the difference between the strike and the rainfall index, the greater the payoff (Stoppa and Hess, 2003; Musshoff *et. al.*, 2009).

$$I_t = \begin{bmatrix} 0 \ \ se \ \ F_t \geq K \\ \dfrac{K - F_t}{K} \ \ se \ \ F_t < K \end{bmatrix} \theta \tag{3}$$

At the limit, considering no rainfall, the producer receives the total indemnity, θ as defined by equation (4):

$$\theta = \left(\frac{1}{5} \sum_{i=1}^{5} Y_{t-i} \right) \times A_t \times P \tag{4}$$

The indemnity calculation takes into account a five-year moving average of crop yields (Y), in kg per hectare. In addition, A_t represents the harvested area in year t and P is the expected price of the soybean at the end of the contract. The price was fixed at US$ 0.346/kg, thus the effect on the producer's financial result is solely a consequence of the change in productivity. In other words, the focus of this study is strictly based on yield risk. The protection against adverse price fluctuations should be done using other risk management tools. This price corresponds to the average of the future prices for soybean nearby futures contracts from the CME Group (Chicago Mercantile Exchange) between 1993 and 2016.

3.2. Option pricing and hedge effectiveness

The option pricing approach is based on index modelling, following Jewson and Brix (2005) and Musshoff *et. al.* (2011)[2]. Firstly, the empirical distribution of the rainfall indexes is derived from the historical data, obtaining the distribution parameters. Given these parameters, 10,000 Monte Carlo simulations are carried out to achieve random values of the rainfall indexes, and then hypothetical payoffs are analyzed. The fair value of the rainfall put-option is the average of the hypothetical payoffs.

The hedging effectiveness is examined by calculating the relative reduction of the producers' risk exposure (standard deviation of the soybean revenue) since using the weather-based derivative. The producer's revenue in year $t(R_t)$ assuming that the rainfall derivative is not used, is given by the farm production φ_t multiplyed by the price of the soybean (P_t) – equation (5). As mentioned in section 3.1, a fixed price is used.

$$R_t = \varphi_t \times P_t \tag{5}$$

With the use of the rainfall put option, the producer's income in year $t(R_t^*)$ is given by equation (6), where the indemnity (I_t), received by the producer in year t, is included, subtracting the premium paid for the weather derivative (pr). Since the option premium is paid for previously, when it is purchased, this amount is updated to the expiration date of the contract, using an annual risk-free interest rate (equal to 4%).

$$R_t^* = R_t + I_t - pr \cdot e^{r \cdot \Delta t} \quad (6)$$

Based on yearly revenues from 1992 to 2016, the average and the standard deviation of these series are obtained comparing the result of the operations with and without the use of weather derivatives. The effect of the basis risk on hedge effectiveness is also investigated, comparing the revenue of the farmers located in cities with weather stations and with no weather stations. Finally, the study investigates the insurance claims, evaluating the indemnities paid and premiums received by the insurance company during the period 1992-2016.

3.3. Data

A dataset of daily precipitation and annual production are used. Six important producing areas in the south of Brazil are considered - Cruz Alta, Santa Maria, São Luiz Gonzaga, Cachoeira do Sul, Tupanciretã, and Vacaria, which are located in the state of Rio Grande do Sul – Appendix Figure A.1. The study focuses on this area because it consists of a traditional soybean producing region, which is characterized by unstable weather, since the climate is subtropical and highly influenced by polar air masses.

In the first three cities, there are rainfall stations. On the other hand, in the last three, there are no stations, being necessary to use the data of the nearest rainfall station. Table 1 presents the distances between these two groups of cities.

The daily precipitation data are provided by the Brazilian Institute of Meteorology (INMET), for the period between January 1st 1992 and December 31st 2016. The soybean production data are obtained from the Brazilian Institute of Geography and Statistics (IBGE) and prices are provided by the CME Group, between 1992 and 2016.

Tab. 1. Distance (in miles) between the cities considered in the study.

	Cities with rainfall station			
	Areas	Cruz Alta	Santa Maria	São Luiz Gonzaga
Cities with no rainfall station	Cachoeira do Sul	105.92	53.69	170.37
	Tupanciretã	35.18	51.51	74.10
	Vacaria	161.54	185.88	246.59

Note: the distances were calculated using the stations' location and the central areas of the cities

4. RESULTS

4.1. Rainfall indexes

Table 2 shows the evolution of the two rainfall indexes during the 1992-2016 period, except for 2001, due to a lack of complete data. The first index, an equal-weighted index, gives the same importance to different cropping periods. The second, a growth-weighted index, takes into account different weights, depending on the stage of the soybean crop cycle. Both indexes were only calculated for three producing areas (Cruz Alta, Santa Maria, Luiz Gonzaga), since these are the only ones with meteorological stations. Results indicate high variability of both indexes. We observe years (for example, 2005 and 2012) with low precipitation and, consequently, low index values. On the other hand, there are years (1998 and 2016) with excessive rainfall, resulting in higher index values.

Tab. 2. Cumulative rainfall indexes between December and March during 1992-2016.

Year	Cruz Alta		Santa Maria		São Luiz Gonzaga	
	Equal-weighted index	Growth-weighted index	Equal-weighted index	Growth-weighted index	Equal-weighted index	Growth-weighted index
1992	70.3	60.2	58.6	58.5	-	-
1993	52.1	65.8	52.6	48.2	54.4	61.0
1994	57.4	40.2	50.6	44.2	66.2	56.4
1995	46.0	57.3	46.6	60.2	43.3	49.9
1996	51.9	48.7	61.1	43.4	62.0	52.8
1997	32.5	28.8	46.3	34.2	49.0	56.5
1998	80.1	62.0	79.1	68.9	95.3	67.7
1999	36.9	43.0	37.4	19.5	35.4	28.8
2000	36.9	43.0	55.1	53.4	53.7	44.3
2002	42.2	36.6	44.7	49.2	46.4	25.3
2003	94.8	94.4	79.0	81.1	71.7	69.2
2004	45.7	38.3	45.0	29.3	37.9	41.8
2005	23.1	20.8	18.9	14.1	31.6	27.4
2006	45.2	45.2	35.4	41.6	43.1	34.9
2007	43.5	48.5	47.2	59.4	61.3	65.7
2008	23.9	32.1	43.4	46.1	35.4	43.8
2009	33.2	39.0	40.9	47.2	28.5	35.8
2010	56.5	67.9	70.6	62.3	75.5	99.0
2011	80.2	77.2	42.1	51.8	54.5	57.4
2012	20.2	18.2	27.2	16.9	16.6	15.3
2013	74.3	83.4	60.4	54.6	76.7	87.7
2014	49.2	50.6	45.5	52.2	54.4	63.1
2015	61.3	87.0	57.4	61.9	71.9	81.5
2016	79.9	91.4	61.3	63.4	94.0	89.2

Tab. 3. Weights for each 10-day period during the soybean crop cycle.

Period	Month											
	December			January			Febuary			March		
	34	35	36	1	2	3	4	5	6	7	8	9
Santa Maria	0.16	0.05	0.06	0.10	0.00	0.00	0.00	0.02	0.25	0.11	0.06	0.19
Cruz Alta	0.00	0.12	0.12	0.19	0.16	0.03	0.00	0.04	0.07	0.12	0.03	0.13
S. L. Gonzaga	0.04	0.14	0.05	0.19	0.13	0.06	0.00	0.14	0.09	0.09	0.03	0.05

Table 3 shows the weights of each of the 12 10-day periods, between December and March, for the growth-weighted index - equation (2). Based on these weights, the index-yield correlation was maximized. In general, the weights were higher at the initial and final stages of the crop cycle, when, respectively, sowing and flowering/physiological maturation of the soybean crop take place. These stages are the most sensitive to water shortages - yield tends to be drastically reduced in case of a water shortage during flowering and physiological maturation of the plant (Mudstock, Thomas, 2005).

The rainfall index-yield correlations are given in Table 4. Taking into account the cities with rainfall station, Santa Maria exhibited the lowest correlations, 0.41 (0.62) for equal-weighted (growth-weighted) index. On the other hand, the cities of Cruz Alta and São Luiz Gonzaga showed higher correlations and smaller differences among each other. The correlation obtained from the equal-weighted index (growth-weighted) exceeded 0.70 (0.85) for both cities - i.e. the rainfall index could explain a significant proportion of yield variations in these areas.

In the cities with no meteorological stations (Cachoeira do Sul, Tupanciretã, Vacaria), we use the index of the closest city with a weather station to obtain the correlations. For Cachoeira do Sul, we assume data from Santa Maria, while for Vacaria and Tupanciretã, we take into account Cruz Alta index (Tab. 2). The highest coefficients were observed in Tupanciretã, given that it is located closer to the station located in Cruz Alta (around 35 miles).

Tab. 4. Correlation coefficient between rainfall index and soybean yield.

	City	Equal-weighted index	Growth-weighted index
With rainfall stations	Santa Maria	0.42	0.63
	Cruz Alta	0.76	0.87
	São Luiz Gonzaga	0.73	0.83
With no rainfall station	Cachoeira do Sul	0.45	0.69
	Tupanciretã	0.68	0.85
	Vacaria	0.54	0.75

As expected, and in line with previous studies (e.g. Stoppa, Hess, 2003; Martin *et. al.*, 2001), the growth-weighted index exhibited higher correlations for all regions of the study. In other words, this index showed better performance in explaining the variability of soybean yield, since it considers different weights for each stage of plant´s growth.

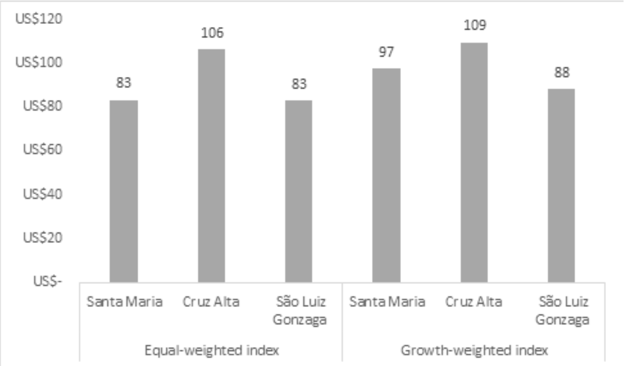
4.2. Premium calculation

In line with the methodology presented by Jewson and Brix (2005), the Jarque Bera, Komogorov-Smirnov and Shapiro-Wilk tests were carried out in order to validate if the rainfall indexes are normally distributed. Considering a 5% significance level, all of the tests indicated that both indexes have normal distribution (Appendices Tab. A.1., A.2. and A.3.). Based on the indexes parameters Monte Carlo simulations were simulated for each of the distributions. For each index, 10,000 simulations were applied and payoffs were obtained for each type of contract. Thus, the fair premium of the derivative was estimated as the expected value of the distribution of the payoffs. Figure 1 shows the estimated average premium paid by the producer.

Overall, the option premium changed according to the structure of the contract. Contracts based on the growth-weighted index were priced higher. This reflected the greater protection capacity of the contract given the higher rainfall index-yield correlation.

In addition, Table 5 shows that the ratio between the option premium and the producer's revenue was higher (lower) for the growth-weighted (equal-weighted) index in the city of Tupanciretã (Santa Maria). Overall, the cost of insurance was very high for all contracts, ranging from 10% to 14% (12% to 15%) of revenue per hectare for the contracts based on equal-weighted index (growth-weighted index).

Fig. 1. Average premium (US$/hectare) of put options during 1992-2016.



Tab. 5. Average ratio between option premium and producer revenue during the 1992-2016 period.

	City	Equal-weighted index	Growth-weighted index
With rainfall stations	Santa Maria	*10.68%*	*12.56%*
	Cruz Alta	*13.97%*	*14.31%*
	São Luiz Gonzaga	*13.83%*	*14.66%*
With no rainfall station	Cachoeira do Sul	*10.84%*	*12.74%*
	Tupanciretã	*14.06%*	*15.14%*
	Vacaria	*14.04%*	*14.38%*

4.3. Weather derivatives performance

A reduction in income variability was verified when the producer used the rainfall put option (Table 6). The revenue fluctuation decreased between 10% and 37%, depending on the city and the contractual structure. The cities in which the index-yield correlation was higher (Cruz Alta, São Luiz Gonzaga and Tupanciretã) showed higher reductions in income volatility - above 20% (30%) for contracts with the equal-weighted index (growth-weighted index).

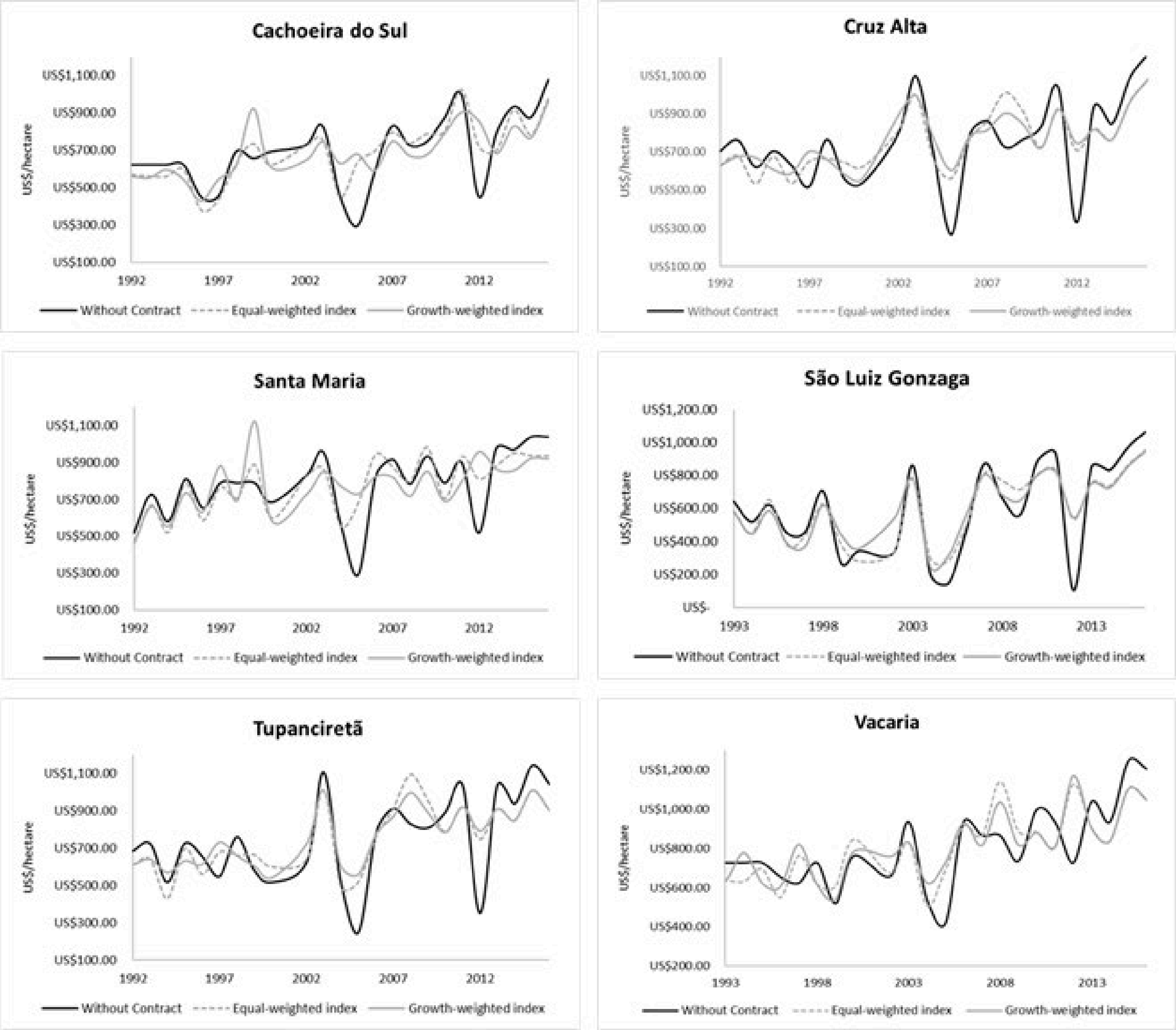
The fall in income variance was larger for the growth-weighted index. The best result occurred in the city of Cruz Alta, exhibiting a reduction of 36.71% (growth-weighted index), while the least expressive result was found in Vacaria, with a reduction of 10.12% (equal-weighted index). The result for Vacaria can be explained by the large distance of this city from the closest meteorological station (around 162 miles). In addition, the amount paid for the rainfall option had no relevant influence on income over time.

Figure 2 shows that the use of weather derivatives stabilized the producer income during the period of 1992-2016. Thus, the use of these contracts would allow a better return predictability of the activity, even in situations of significant water shortage. In certain years, 2005 and 2012, rainfall showed a relevant decrease, resulting in significant reductions in soybean productivity among the regions. Thus, this would particularly affect those producers that did not adopt the rainfall put option. However, the contracts based on an equal-

Tab. 6. Average standard deviation of income per hectare (US$/hectare) and average income per hectare (US$/hectare) from 1992 to 2016.

City	Without contract ($/hectare) (A)	With contract / Equal-weighted index ($/hectare) (B)	Percent change (B *versus* A)	With contract / Growth-weighted index ($/hectare) (C)	Percent change (C *versus* A)
Average standard deviation of income					
Cachoeira do Sul	191.07	160.68	*-15.90%*	136.59	*-28.51%*
Cruz Alta	226.97	158.44	*-30.20%*	143.64	*-36.71%*
Santa Maria	185.27	152.20	*-17.85%*	144.35	*-22.03%*
S. L. Gonzaga	282.37	212.47	*-24.76%*	194.26	*31.20%*
Tupanciretã	237.33	182.18	*-23.24%*	154.34	*-34.97%*
Vacaria	202.53	182.03	*-10.12%*	166.83	*-17.63%*
Average income					
Cachoeira do Sul	693.37	694.68	*0.19%*	699.31	*0.86%*
Cruz Alta	754.87	759.82	*0.66%*	763.38	*1.13%*
Santa Maria	777.83	777.68	*-0.02%*	775.65	*-0.28%*
S. L. Gonzaga	598.65	598.31	*-0.06%*	600.92	*0.38%*
Tupanciretã	750.15	752.96	*0.37%*	756.86	*0.89%*
Vacaria	800.63	801.6	*0.12%*	805.46	*0.60%*

Fig. 2. Evolution of income per hectare (US$/hectare) by city from 1992 to 2016.



weighted index and growth-weighted index were able to maintain soybean crops revenue at historical levels.

The analysis of average contractual claims shows the potential financial sustainability of the operation from the point of view of insurance companies. During the 1992-2016 period, the average of the indemnity-premium ratio exceeded 100% for most of the contracts based on the growth-weighted index, albeit by a narrow margin. Table 7 indicates the years in which these ratios exceeded 100%, showing that the contract could provide highly negative financial results for the insurance company, despite being compensated for in other periods (years). These simulations ignored the administrative costs and profits for the insurance companies. As an alternative to resolving these issues, the insurance companies could vary the strike price, adjusting the risk of the contract. However, on the other hand, this adjustment would result in a lower hedge performance for the farmer.

Finally, the impact of the distance of the weather station on hedge effectiveness was relevant, in agreement with Woodard and Garcia (2008a), pointing that the remote weather stations would entail high transaction costs and render contracts infeasible. As shown in Table 8, hedge effectiveness decreased significantly when the distance was greater than 150 miles from the station used for data collection.

For the city of Vacaria, where all stations are located more than 150 miles away, none of the contracts were

Tab. 7. Average of the indemnity-premium ratio during the 1992-2016 period.

City	Equal-weighted index	Growth-weighted index
Cachoeira do Sul	*93.18%*	*91.87%*
Cruz Alta	*99.60%*	*104.10%*
Santa Maria	*93.18%*	*91.87%*
São Luiz Gonzaga	*96.92%*	*100.35%*
Tupanciretã	*99.61%*	*104.12%*
Vacaria	*99.61%*	*104.12%*

able to reduce volatility by more than 20%. In addition, the contract based on the furthest station (São Luiz Gonzaga, approximately 247 miles away) presented the worst result for both indexes. On the other hand, the city of Tupanciretã, which has three stations under 75 miles away presented a decrease in the income standard deviation of more than 25%, using the growth-weighted index. The highest value, at almost 35%, was found when the rainfall index from the closest station (Cruz Alta) was used.

The results obtained confirm the hypothesis that the basis risk must be treated with caution when creating weather derivatives based on rainfall indexes. This is due to the existence of different edaphoclimatic structures in the regions considered. Overall, findings suggest that hedge effectiveness was reduced when the distances between the producing areas and the weather station were higher, as shown by Woodard and Garcia (2008a; 2008b) and Deng *et. al.* (2007). However, this loss is only relevant for large distances, which would be easily mitigated by installing meteorological stations in different regions, resulting in a fall in the contracts' basis risk (Collier *et. al.*, 2009).

5. CONCLUSIONS

The use of weather derivatives as risk management tools in Brazilian agribusiness is almost non-existent. Thus, the development of new and more efficient contracts can result in new elements to improve producers' decisions and to benefit the management of agricultural activity. In this context, this study analyzed the viability of using rainfall put options as a risk management tool in southern Brazilian soybean production.

A put option was structured with the underlying asset based on two types of rainfall indexes: growth-weighted and equal-weighted. Findings showed that the growth-weighted index exhibited greater hedging efficiency. The pricing of the contracts reflects this fact, given the higher premiums for this type of insurance. Similar results were obtained by Stoppa and Hess (2003), Pelka and Musshoff (2013), Shi and Jiang (2016) and Torriani *et. al.* (2018) when analyzing the crop production risks in several markets.

Using a rainfall derivative, producers were able to reduce their climate risk, resulting in a significant fall in income variation per hectare. A large proportion of the producers' losses during periods of low rainfall were recovered, without a decrease in income. However, the cost of insurance was high for all contracts simulated in the study, ranging from 10% to 15% of revenue per hectare. In addition, with regards to the financial sustainability of the contract, results suggest that without a risk adjustment the contract can be unsustainable in the long run, since the indemnity-premium ratio exceeded 100% in most of the growth-weighted contracts.

Finally, we also observed that basis risk is a key challenge for weather-based derivatives. The hedging effectiveness was lower when distances were above 150 miles from the meteorological stations used in the contract. These results reinforce the importance of well-designed contracts developed for hedging weather issues in the agricultural markets. Regions with different climatic conditions or distinct geographical characteristics can be affected differently by rainfall patterns and cause a significant change in hedge effectiveness, according to the findings of Musshoff *et. al.* (2011).

The study provides useful insights for risk management strategies adopted by producers, insurance companies and other players along the soybean production

Tab. 8. Average variation in the standard deviation of income per hectare from 1992 to 2016.

	Cruz Alta		Santa Maria		São Luiz Gonzaga	
	Equal-weighted index	Growth-weighted index	Equal-weighted index	Growth-weighted index	Equal-weighted index	Growth-weighted index
Cachoeira do Sul	*-15.04%*	*-26.99%*	*-15.90%*	*-28.51%*	*-16.37%*	*-12.63%*
Tupanciretã	*-23.24%*	*-34.97%*	*-19.78%*	*-33.22%*	*-20.58%*	*-25.82%*
Vacaria	*-10.12%*	*-17.63%*	*-12.44%*	*-19.46%*	*-9.93%*	*-10.24%*

chain. Insights from this research can be particularly helpful for policy makers in the conduction of agricultural policies related to risk management. In this context, previous studies have indicated the key role of the institutional and regulatory environment in stimulating insurance and related markets (Stoppa and Hess, 2003; Leblois and Quirion, 2013; Henderson, 2002).

The findings of this study may also be relevant for soybean market players in Argentina and Paraguay, since part of their production is located near the areas considered in this study. Thus, the development of a weather contract based in south of Brazil can, at least partially, help a number of players located in these countries to manage their risks.

Finally, the results provide interesting points for academic discussion regarding weather derivatives and their use in agricultural activity. Future research can explore the potential benefits and limitations of the weather derivatives in hedging strategies for several crops and areas. Moreover, an important issue to investigate is the analysis of the adoption of mixed-based weather derivatives, which in turn use composite weather indexes, considering the potential to reduce basis risk. Further, the efficiency of these strategies can be evaluated from the insurers' perspectives, investigating the financial sustainability of these operations.

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APPENDIX

Tab. A.1. Jarque-Bera tests.

City	Index	Obs.	Pr(Skewness)	Pr(Kurtosis)	adj chi2(2)	Prob>chi2
Cruz alta	Equal-weighted	24	0.3408	0.6378	1.2200	0.5427
	Growth-weighted	24	0.3459	0.4768	1.5200	0.4671
Santa Maria	Equal-weighted	24	0.7250	0.5101	0.5800	0.7470
	Growth-weighted	24	0.2455	0.6224	1.7500	0.4178
S. L. Gonzaga	Equal-weighted	23	0.6483	0.7062	0.3600	0.8367
	Growth-weighted	23	0.5893	0.6981	0.4600	0.7959

Tab. A.2. Shapiro-Wilk tests.

City	Index	Obs.	W	V	z	Prob>z
Cruz alta	Equal-weighted	24	0.9593	1.0980	0.1900	0.4247
	Growth-weighted	24	0.9554	1.2030	0.3770	0.3532
Santa Maria	Equal-weighted	24	0.9697	0.8170	-0.4130	0.6601
	Growth-weighted	24	0.9525	1.2810	0.5050	0.3068
S. L. Gonzaga	Equal-weighted	23	0.9751	0.6520	-0.8680	0.8074
	Growth-weighted	23	0.9797	0.5310	-1.2870	0.9010

Tab. A.3. Komogorov-Smirnov tests.

City	Smaller Group	Equal-weighted index		Growth-weighted index	
		D	p-value	D	p-value
Cruz Alta	Simple	0.1145	0.5330	0.1332	0.4270
	Cumulative	- 0.0876	0.6920	-0.0840	0.7120
	Combined K-S	0.1145	0.9110	0.1332	0.7880
Santa Maria	Simple	0.1250	0.4740	0.0973	0.6350
	Cumulative	- 0.0910	0.6700	-0.1311	0.4380
	Combined K-S	0.1250	0.8490	0.1311	0.8040
S. L. Gonzaga	Simple	0.0915	0.6810	0.0781	0.7550
	Cumulative	- 0.0689	0.8040	-0.0651	0.8230
	Combined K-S	0.0915	0.9910	0.0781	0.9990

Fig. A.1. Geographical location of the cities considered in the study.