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## RAINFALL EFFECT ON SOYBEAN PRODUCTION IN PARAGUAY, STATISTICAL ANALYSIS, AND MODELING DEVELOPMENT TO MITIGATE RISK

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The title of this dissertation is “Rainfall Effects on Soybean Production in Paraguay, Statistical Analysis and Modeling Development to Mitigate Risk”. The main purpose of this research is to find a strategy to decrease the chances of counterproductive inter-annual variances in soybean’s yield (yield per hectare). This study was motivated by a deep concern regarding the lack of research explaining the causes of high volatility in soybean yield in Paraguay. Because of the relevance of soybean production in this country, its volatility is negatively impacting the whole economy.

Based on statistical analysis, causes of high inter-annual fluctuations in yield are dimed to rainfall conditions, more specifically in two: (i) in-season rainfall magnitude and (ii) shape of rainfall cumulative distributions. The main contribution of this research would be the introduction of the Accumulated Rainfall Concavity Pattern Index (ARCPI), which depicts a range of cumulative rainfall scenarios, from bad to efficient, giving the chance to monitor cumulative rainfall distributions and respond on-time, adapting to mitigate negative impacts.

There are six specific objectives of this study, (1) Conduct statistical analysis on main climate factors affecting soybean productivity, (2) To model response functions, enabling us to predict yield in a simple but robust manner, (3) To establish a strategy that could help to manage the environmental factor associated to yield volatility, (4) To conduct a counterfactual analysis, to show how the management of the specific factor could modify yield, (5) To design and propose mechanisms to implement models and findings developed in this thesis and suggest irrigation as a risk management tool, and (6) To propose policy recommendations related to risk management in soybean production in Paraguay.

In Chapter 1 we explain the evolution and relevance of soybean production around the world and Paraguay. We review risk management in soybean production by presenting sources of risk from two perspectives; (i) abiotic and biotic factors, and (ii) environmental sources of stress. Later, we depict soybean production in Paraguay, specifically current challenges that are partially addressed by this research. Also, we raise the need for awareness of risk management from public policy approaches. We formulate a list of research problems, leading us to six research objectives, used to set the research framework. Main literature to feed this thesis is organized to identify research gaps, setting the justifications, motivations, and foundations for this work. Also, we outline the content of this thesis.

In Chapter 2, we present the data sources of this analysis; they are two databases compiling production and climate data. Production data was provided by the Department of Census and Statistics of the Ministry of Agriculture and Livestock, meanwhile, daily climate data was produced

and later provided by the Risk Management Unit (hereinafter UGR by its acronym in Spanish) under the Ministry of Agriculture and Livestock (hereinafter MAG by its acronym in Spanish) of Paraguay. Data presented here are temperature and rainfall from 1991/2 to 2013/4. At the end of this chapter, we present a basic analysis of how temperature and rainfall could be connected to yield, showing apparent correlation or not.

In Chapter 3, we introduce a segmented linear model to explain yield from average daily rainfall as a primary source of analysis. We termed this model “Base Model”. Furthermore, we analyze cumulative rainfall patterns to find four types of patterns named: (1) Good, (2) Bad, (3) Efficient and (4) Inefficient. The occurrence of concave cumulative rainfall patterns is observed to be counterproductive for attaining good yield.

In Chapter 4, based on pattern analyses in the previous chapter, we introduce an index to measure concavity of cumulative rainfall curve named ARCPI (Accumulative Rainfall Concavity Pattern Index). In order to analyze the relation between ARCPI and residuals of the Base Model, we divide data into three categories, Categories 1, 2 and 3 according to average daily rainfall, as follows: (i) less or equal to 5.5 mm/day, (ii) greater to 5.5 mm/day and lower than 6.4 mm/day, and (iii) greater than 6.4 mm/day. It is observed that higher ARCPI tends to imply lower yield. We show how ARCPI can be applied to make a decision on what to do to minimize the risk of low yield (below 2,000 kg/ha).

In Chapter 5, we develop three linear regression models to predict yield for each of the three categories, Category 1-3. The regression model for Category 1 uses the average daily rainfall throughout the whole campaign and ARCPI as explanatory variables. The model for Category 2 uses the average rainfall data in September, October, November, and ARCPI as explanatory variables, meanwhile the model for Category 3 uses the average daily rainfall in September and ARCPI as explanatory variables. Models and concepts in Chapters 3-5 lead to the following interesting and crucial findings:

- (1) Yield per hectare increase monotonically (linearly) as daily average rainfall increases. After attaining a maximum, it declines also monotonically.
- (2) A concave-shaped pattern of cumulative rainfall curve is in general counterproductive, regardless of the amount of rain, leading to the creation of ARCPI.
- (3) If cumulative rainfall around 80 days after sowing is between 300 to 550 mm, the yield can be low with considerable probability.

In Chapter 6, we demonstrate that irrigation can be a suitable mechanism to manage climate risk. In order to show how the models developed in Chapter 5 can be used to calculate the change of costs and revenues for irrigation, we conducted a counterfactual analysis using the situation occurred in Itapúa in 2012. In reality, the net income for this prefecture was only 63.13USD/ha in 2012. Our counterfactual analysis result shows that gains via irrigation could have reached 155.22 USD/ha if we irrigate 1 mm/day for 73 days, and 222.16 USD/ha for 2 mm/day for 73 days. The counterfactual analysis shows encouraging results and raises a red flag about prices (market risk), suggesting that further analysis should be done separating market risk and climate risks scenarios. The result indicates that irrigation can be introduced as a public policy mechanism

to protect the sector and country from climate risk specifically rainfall scarcity and unstable patterns.

In Chapter 7, we introduce a field experiment which is conducted by FECOPROD and Instituto Desarrollo (iD) to confirm the model and findings obtained so far. The experiment will reject or fail to reject the following hypothesis: (i)  $ARCPI \geq 0.16$  produce lower average soybean's yield, (ii) Day 80 is the breaking point for decision making, (iii) The controlled increment of water supply by irrigation leads to greater and stable yield, (iv)  $Insurance\ Cost \geq Irrigation\ Cost \leq Losses$  (Remission of Debt and/or Debt re-financing).

In Chapter 8, we propose the design of a public policy mechanism that should be put in place with the objective of promoting the use of irrigation systems. Purchase of irrigation systems will produce a positive impact on productivity of soybean-like crops (wheat, corn, sunflower, etc.) since the irrigation equipment needs no further modification to be implemented on those additional crops, therefore the hit of the implementation cost could be absorbed by a set of investments (portfolio) minimizing the toll of the initial cost.

In Chapter 9, we present results and conclusions of the whole thesis, summarizing models and main findings of this research.