EVALUATION OF INTERPOLATED RAINFALL DATA FOR WEATHER INDEX INSURANCE SPATIAL BASIS RISK MANAGEMENT IN THE MUDA IRRIGATION AREA, KEDAH, MALAYSIA

By

MUKHTAR JIBRIL ABDI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

January 2023

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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Chair : Zed Diyana Zulkafli, PhD
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Weather index insurance allows small-scale farmers to secure income fluctuations caused by adverse weather conditions. However, the problem of basis risk hinders the demand for weather index insurance by farmers, while the systemic weather risk problem impedes the supply of weather index insurance by insurers. This work aimed to construct a hypothetical weather index insurance that protects small-scale rice farmers against extreme weather-induced risks for the Muda Agricultural Development Authority (MADA) in north-western Peninsular Malaysia. We first developed a monthly rainfall dataset over the Muda area for 16 years (2001-2016) using different spatial interpolation methods such as Nearest Neighbour (NN), Inverse Distance Weighting (IDW), Ordinary Kriging (OK), and Kriging with External Drift (KED). The performance of the methods was evaluated and compared in a cross-validation framework using the Root Mean Square Error (RMSE) and Relative Root Mean Square (RRMSE). We then derived various climate indices that include cumulative rainfall (CR) based on interpolated rainfall data and rainfall data from a rainfall station located in the centre of the insured area, cumulative Growing Degree Days (GDD), Standardised Precipitation Index (SPI) at different time scales, and average relative humidity. The CR, GDD, and humidity indices were derived at monthly, mid-season and seasonal time scales. The correlation between these indices and seasonal rice yield (e.g, off-season, and main season) at different levels of spatial aggregation was then analysed. A separate hypothetical index insurance contract for each season and area was developed, and their risk reduction potential was evaluated by comparing granary level contracts with sub-granary level contracts and interpolated-based rainfall contracts with station-based rainfall contracts. We found that the IDW2 method was the best approach to interpolate rainfall data, as evidenced by the RMSE and RRMSE, followed by IDW3, OK, and KED, while the NN method performed the worst. For the results of the correlation analysis, the GDD indices in June were mainly associated with rice yield in the dry off-season across most of the areas. Moreo-

ver, cumulative rainfall (i.e, CR_station and CR_interpolated) and SPI1 indices in December were mainly associated with rice yield in the wet main season across most areas. In GDD-based contracts of the dry off-season, the standard deviation reduction (average of all sub-granaries) at the sub-granary level was less than the standard deviation reduction at the granary level by approximately 28%, revealing an increased risk reduction potential at higher levels of spatial aggregation compared to lower levels. In CR-based contracts of the wet main season, a marginal risk reduction potential was achieved at higher levels of aggregation using rainfall-based contracts, compared to a higher risk reduction potential achieved with temperature-based contracts in off-season. The use of the CR_interpolated index did not reduce spatial basis risk at both granary and sub-granary levels. The developed methodology, which analyses spatial basis risk using various interpolation methods, could serve as a foundation for future research on rainfall index insurance. This work could help farmers and policy makers with their risk management plans for rice production to respond to crop losses related to extreme weather.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENILAIAN DATA HUJAN YANG TERSISIP BAGI PENGURUSAN RISIKO ASAS RUANGAN INSURANS BERASASKAN INDEKS CUACA DI KAWASAN PENGAIRAN MUDA, KEDAH, MALAYSIA

Oleh

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Insurans berasaskan indeks cuaca membolehkan petani kecilan menjamin pendapatan yang tidak menentu disebabkan oleh cuaca buruk. Namun begitu, masalah risiko asas menyekat tuntutan insurans berasaskan indeks cuaca oleh petani, bilamana masalah risiko cuaca sistemik menghalang penawaran insurans berasaskan indeks cuaca oleh syarikat insurans. Matlamat kajian ini adalah untuk membina insurans berasaskan indeks cuaca hipotesis yang melindungi pesawah kecilan daripada risiko akibat cuaca yang melampau bagi Lembaga Kemajuan Pertanian Muda (MADA) di barat laut Semenanjung Malaysia. Kami terlebih dahulu menghasilkan set data hujan bulanan di kawasan Muda bagi tempoh 16 tahun (2001-2016) dengan menggunakan kaedah interpolasi ruangan beza seperti Titik Terdekat (NN), Pemberat Jarak Songsang (IDW), Kriging Biasa (OK), dan Kriging berserta Hanyutan Luaran (KED). Prestasi kaedah tersebut telah dinilai dan dibandingkan dalam sebuah rangka kerja pengesahan silang dengan menggunakan Ralat Punca Min Kuasa Dua (RMSE) dan Punca Min Kuasa Dua Relatif (RRMSE). Kami kemudiannya membuat pelbagai indeks iklim yang merangkumi hujan kumulatif (CR) berdasarkan data hujan yang tersisip dan data hujan dari sebuah stesen hujan yang terletak di tengah-tengah kawasan yang diinsuranskan, kumulatif Hari Darjah Pertumbuhan Kumulatif (GDD), Indeks Kerpasan Standard (SPI) pada skala masa yang berbeza, dan purata kelembapan relatif. Indeks CR, GDD dan kelembapan diperoleh secara bulanan, pertengahan musim dan skala masa bermusim. Korelasi antara indeks-indeks ini dan tuaian padi bermusim (contohnya, pada masa luar musim dan musim utama) dianalisis kemudiannya pada pelbagai peringkat pengagregatan. Kontrak insurans indeks hipotesis yang berasingan bagi setiap musim dan kawasan telah dibangunkan, dan keupayaan pengurangan risikonya telah dinilai dengan membandingkan kontrak peringkat jelapang dengan kontrak peringkat sub-jelapang serta kontrak hujan berasaskan interpolasi dengan kontrak hujan berasaskan stesen. Kami mendapati bahawa kaedah IDW2 merupakan pendekatan terbaik untuk menyisipkan data hujan, seperti yang telah dibuktikan oleh RMSE dan RRMSE, diikuti oleh IDW3, OK, dan KED.

Akan tetapi, kaedah NN merupkan pendekatan yang kurang baik. Keputusan analisis korelasi menunjukkan indeks GDD pada bulan Jun kebanyakannya dikaitkan dengan tuaian padi pada luar musim kemarau di kebanyakan kawasan. Tambahan pula, hujan kumulatif (cth., CR_stesen dan CR_tersisip) dan indeks SPI1 pada bulan Disember kebanyakannya dikaitkan dengan tuaian padi pada musim hujan utama di setiap kebanyakan kawasan. Dalam kontrak berasaskan GDD pada luar musim kemarau, pengurangan sisihan piawai (purata semua sub-jelapang) di peringkat sub-jelapang adalah kurang daripada pengurangan sisihan piawai di peringkat jelapang sebanyak lebih kurang 28%. Ini menunjukkan peningkatan keupayaan pengurangan risiko pada peringkat pengagregatan ruangan yang lebih tinggi berbanding dengan peringkat yang lebih rendah. Dalam kontrak berasaskan CR pada musim hujan utama, keupayaan pengurangan risiko marginal dicapai pada peringkat pengagregatan yang lebih tinggi melalui kontrak berasaskan hujan, berbanding dengan keupayaan pengurangan risiko yang lebih tinggi dicapai dengan kontrak berasaskan suhu pada luar musim. Penggunaan indeks CR_tersisip tidak mengurangkan risiko asas ruangan pada kedua-dua peringkat jelapang dan sub-jelapang. Metodologi yang dibangunkan ini menganalisis risiko asas ruangan dengan menggunakan pelbagai kaedah interpolasi. Metodologi ini boleh digunakan sebagai asas untuk penyelidikan insurans berasakan indeks hujan pada masa hadapan. Kajian ini dapat membantu petani dan pembuat dasar membuat rancangan pengurusan risiko mereka untuk pengeluaran padi bagi menangani kerugian hasil tuaian yang disebabkan oleh cuaca buruk.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my gratitude to Allah SWT, the Almighty, for His blessings throughout my research work that enabled me to successfully complete this study.

I extend my deep and sincere appreciation to my research supervisor, Assoc. Prof. Dr. Zed Diyana Zulkafli, for providing me with the opportunity to conduct this research under her guidance and for her invaluable support and guidance throughout my work. Working and learning under her supervision was a great privilege and honour. I am also grateful to my supervisory committee members, Assoc. Prof. Dr. Farrah Melissa Muharam and Dr. Nurulhuda Khairuddin, for their continuing support, which was crucial to the completion of this work.

I would like to express my sincere appreciation to my mother, cousin, and siblings for their unwavering love, support, prayers, care, and sacrifices in preparing me for my future. I am also grateful to my friends and research colleagues for their constant encouragement and support.

Finally, I would like to express my gratitude and appreciation to all the individuals who supported me directly or indirectly during my research work, particularly the lecturers and staff members of the Department of Civil Engineering, Faculty of Engineering, University Putra Malaysia.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Rice is the main staple food for the majority of Malaysians and the main source of revenue and livelihood for small-scale farmers (Siwar et al, 2014). In 2016, Malaysia shared 2.2% of the world's total rice imports. The recorded rice consumption per capita was 83.9 kg per year, which is equivalent to an average of two and a half plates of rice per person per day (Omar et al, 2019). The sustainability of Malaysia's paddy and rice industry has become the bottom-line in achieving food security and addressing poverty (Siwar et al, 2014). Like many other food crops, rice cultivation is exposed to extreme climate events. Climate change- and variability-induced rainfall variability and higher temperature records adversely affect rice production. Several studies that have been conducted in Malaysia have agreed on the negative influence of climate change on rice yield (Vaghefi et al, 2011, 2013, 2016).

Throughout the thesis, various terms associated with the concept of "risk" will be used. Therefore, it is essential to define the term "risk" and other terms that fall under its umbrella before proceeding further. According to Mitkov (2016), risk is “the potential danger of an event causing damage to a particular object”. Agricultural risks are complex and unpredictable factors as a result of a variety of climatic and biological factors (Komarek et al, 2020). These risks can manifest in various types, including production risk, market risk, financial risk, institutional risk, and personal risk (De Mey et al, 2016; Komarek et al, 2020). Production risk refers to the situation where crop yield growth is highly volatile due to unpredictable external factors such as climate, pests, and disease (Baethgen et al, 2008). Insurers commonly face systemic weather risk, which refers to unfavourable weather conditions such as droughts, floods, or extreme temperatures that affect a large geographical area (trading area of the insurance) (Miranda & Farrin, 2012). Finally, basis risk is related to the design of weather index insurance and refers to the imperfect correlation between the weather index and the risk it aims to protect against (Hess et al, 2002).

The policy interventions for rice production by the Malaysian government are primarily developed to meet three main objectives. Firstly, securing food production is the main objective and can be achieved by maintaining a reasonable self-sufficiency level of 65%. Secondly, boosting productivity and farmers' income to make paddy cultivation financially achievable and supporting the rice sector by controlling the price of farm productions to increase farmers' income by providing input subsidies, particularly fertilisers, and to minimise production costs. Thirdly, securing a sufficient food supply with stable and fair prices for consumers, particularly low-income consumers, and it can be achieved by allowing market forces to regulate the quality and price of rice (Vaghefi et al, 2016).

Furthermore, to adapt to climate change, the government's current farm-level strategies primarily focus on two aspects. Firstly, increasing farmers' awareness about the current and future risks of climate change and informing them of the necessary adaptation actions to respond to these risks. Secondly, securing the farm and farmers' income if the crop is damaged (Alam et al, 2012). For example, the government spends considerable compensation for post-disaster relief in agriculture after flooding (Alam et al, 2020).

The use of crop insurance as an ex-ante risk management mechanism is a viable alternative for risk transfer in Malaysia. Crop insurance has been adopted in various countries. By adopting crop insurance, the government's intervention in rice production could be limited, resulting in a reduction of ex-post costs borne by the government (World Bank, 2011).

Two types of crop insurance exist: indemnity-based insurance and index-based insurance. The payout in traditional indemnity-based insurance is calculated by assessing the farm losses in the area affected by a bad climate event, while the payout in index-based insurance is calculated based on an independent proxy for yield loss, that is, weather index (World Bank, 2011). Skees et al. (1999) have proposed the idea of index-based insurance to serve as a risk management tool for developing countries. During the first decade after its proposal, there have been more than 30 weather index insurance pilots in developing nations (Collier et al, 2009). Since then, the literature on weather index insurance has mainly focused on the problems related to weather index insurance such as basis risk, data scarcity and systemic weather risk, and the methodological aspect of designing weather index insurance (Musshoff et al. 2011; Turvey and Mclaurin, 2012; Elabed et al, 2013; Leblois et al, 2014a; Conradt et al, 2015a; Bokusheva et al, 2016; Dalhaus & Finger, 2016; Okpara et al, 2017; Dalhaus et al, 2018; Shirsath et al, 2019; Hohl et al, 2020; Salgueiro & Tarrazon-Rodon, 2021). Weather index insurance, however, is vulnerable to a basis risk, which impedes its demand by agricultural producers (Clement et al, 2018). Another problem associated with the supply of crop insurance is systemic weather risk (Miranda & Farrin, 2012).

There are three types of basis risk, namely, design, spatial and temporal. Design basis risk is characterized by a weak relationship between the crop yield and the weather index (Leblois et al, 2014a); temporal basis risk is a result of imperfect selection of the time window that captures critical crop growth stages for deriving the index (Leblois et al, 2014b); and spatial basis risk is a result of the distance between the point where the weather index is monitored and the location of the insured farm (Dalhaus & Finger, 2016).

There are different strategies suggested to reduce the different types of basis risk. Conradt et al, (2015a) suggested improving the yield-index relationship using statistical methods such as quantile regression and copula to reduce the design basis risk, while the use of flexible time windows rather than fixed time windows based on crop growth phases (Conradt et al, 2015b) was suggested to reduce temporal basis risk. To reduce the spatial basis risk, weather index observed from a nearby station or station that is geographically located in the centre of the insured area could be used (Vedenov and Barnett 2004;Woodard & Garcia, 2006). Chen et al, (2017) suggested the interpolation of station rainfall data, while Dalhaus and Finger (2016) suggested the use of freely accessible to public interpolated (gridded) rainfall data.

Duncan & Myers (2000) argued that systemic weather risk in agriculture is the main inhibiting factor of the private insurance market providing crop insurance. The optimal requirement for insurance markets to exist and function effectively is that idiosyncratic risks has to be uncorrelated and occur with high frequency (Miranda & Farrin, 2012; Salgueiro & Tarrazon-Rodon, 2021). Insurance providers could use weather index insurance as a reinsurance tool to reduce their exposure to the systemic weather risk problem (Miranda & Gonzalez-Vega, 2011). Some studies found that using yield data spatially aggregated at higher levels (e.g, from farm level to district/county level) could increase the risk reduction potential of weather index insurance (Woodard and Garcia, 2006; Weber et al, 2015), consequently reducing the systemic weather risk problem faced by insurance providers.

1.2 Problem statement

Climate change- and variability-induced adverse weather events (i.e, floods and droughts) cause massive crop losses in Malaysia. Historical climate variables such as low and high temperatures, excessive and deficit rainfall, and other extreme weather events significantly affect rice crop production, consequently challenging food security (Firdaus et al, 2020; Zulkafli et al, 2021). Projected increased temperature trends and changing rainfall patterns would have a mixture of negative and positive impacts on rice in Malaysia (Vaghefi et al, 2016; Tan et al, 2021; Houma et al, 2021). In the case of the Muda irrigation area, extreme rainfall trends have caused significant flood events in the years 2003, 2005, and 2017, which caused massive yield losses (Firdaus et al, 2020). In response to these losses, the Malaysian government spends a considerable amount of subsidies and post-disaster relief funds in the agriculture sector (Omar et al, 2019; Alam et al, 2020). Climate adaptation and agricultural risk management tools need to be incorporated with more risk transfer tools. Weather index insurance, if properly designed, is a risk transfer tool that can allow small-scale farmers to protect their paddy production from losses caused by adverse weather conditions. However, the literature related to weather index insurance is limited in Malaysia, and this gap needs to be filled before it can practically occur.

In Malaysia, weather index insurance has been the subject of a few studies (Taib & Benth, 2012; Wen et al, 2019; Alam et al, 2020; Zulkafli et al, 2021). A pilot-scale study investigating the weather index insurance for paddy farmers in five selected states across Malaysia used temperature and rainfall indices and found that the yield in three paddy cultivation area zones was not adequately correlated with the evaluated indices (Wen et al, 2019). Before that, Taib & Benth (2012) analysed the pricing of weather insurance using a cooling degree days-based index and three different pricing methods; however,the study did not consider the aspect of yield-index modelling. Neither of these two studies evaluated the risk reduction potential of weather index insurance in Malaysia. Recently, Zulkafli et al. (2021) investigated the influence of different hydroclimatic variables on rice production in the Muda area and found that the minimum temperature and the average streamflow were strongly correlated with rice yield. Despite these findings, the work did not develop a weather index contract. Evaluation of the risk reduction potential of weather index insurance in the Muda irrigation area is an important question, particularly for the small-scale tropical rice production systems in developing countries, that warrant further study.

Spatial basis risk occurs when the weather conditions recorded at a rainfall station differ from the actual weather conditions experienced on the farm. This happens when the rainfall station used in the contract design is remote from the farm location and insufficiently depicts the weather situation at the farm (Leppert et al, 2021). In this case, interpolating the data from existing rainfall stations may provide advantages such as improving the spatial coverage of the rainfall data and better capturing the rainfall patterns in the farm area. Therefore, testing whether interpolated data for rainfall (versus rainfall station data) can reduce spatial basis risk and thereby improve the performance of weather index insurance may require further study. It is also important to evaluate the performance of various interpolation methods before using the interpolated rainfall data generated by the method with the highest accuracy for weather index insurance design. This is particularly related to the density of the station network available in the study area. IDW and NN methods are superior when the rainfall station density is high, OK, and KED methods are superior when the rainfall stations density is low (Goovaerts, 2000; Akhtari et al, 2009).

1.3 Research Hypothesis

The following hypothesis was to be tested in this study:

1) IDW method is likely to perform better than other interpolation methods (NN, OK, and KED) in densely gauged areas.
2) Temperature is associated with rice yield in the off-season, while rainfall is associated with rice yield in the main season.
3) The risk reduction potential of weather index insurance i) using crop yield data observed from high levels of aggregation is higher compared to crop yield data observed from high levels of aggregation, and ii) using interpolated rainfall observations is higher compared to rainfall observations from a station located in centre of the insured area.

1.4 Research Objectives

This main objective of this study was to develop a weather index insurance protecting rice farmers against extreme weather-induced production losses in Malaysia's Muda rice area and investigate the spatial basis risk and spatial aggregation effect.

Specific objectives:

1) To establish a gridded total monthly rainfall dataset over the Muda area using interpolation methods by quantifying and comparing their performance for 16 years (2001-2016).
2) To derive climate indices for the Muda granary and its sub-granaries by analysing their correlation with seasonal yield data at different levels of spatial aggregation.
3) To evaluate the risk reduction potential of a weather index insurance contracts by comparing granary level contracts with sub-granary level contracts for off-season and main season and interpolation-based rainfall contracts with station-based rainfall contracts for the main season.

1.5 Scope of the study

This work aimed to construct a hypothetical weather index insurance contract that protects small-scale rice farmers against extreme weather-induced risks for the Muda irrigation area. Weather index insurance contracts were developed for both the off-season and main season. In the Muda area, the drier off-season begins in March and ends in July, while the wetter main season starts in September of the same year and ends in January of the subsequent year.

Historical data on rainfall and seasonal rice yield, maximum and minimum temperature, and humidity were collected from Muda Agricultural Development Authority (MADA) and Department of Irrigation and Drainage Malaysia (DID) and Malaysian Meteorological Department (MMD), respectively. Rainfall data was collected from 60 observation stations, while temperature and humidity data were collected from two stations. The data collected period extended over 16 years from 2001 to 2016.

The Muda area was selected as the study area due to the lack of prior research on the performance of weather index insurance at the rice production area scale. Muda area is the largest rice-producing granary in Malaysia, accounting for approximately 38.8% of the country's rice production. In the context of agriculture in Malaysia, a granary refers to a specific area of land that is reserved for cultivating rice crops, as stated in the literature (Omar et al, 2019). Currently, there are eight granary areas designated for rice cultivation in Malaysia, including the Muda area. Within the Muda area, the rice fields are managed by four districts, namely, Arau, Jitra, Pendang, and Kota Sarang Semut, which are referred to as sub-granaries in this work. Therefore, a sub-granary is a district within a designated granary area that is responsible for managing the cultivation of rice crops in a specific area.

It is important to recognise that this thesis has several limitations that should be acknowledged. Firstly, due to the limited availability of yield and climate data, our analysis was limited to a 16-year time series. However, for a more comprehensive understanding of the impact of extreme weather events on crop yields, at least 30 years of data would be ideal. Another limitation was the inaccessibility of yield data at the individual farmer organisation (PPK) level, despite the presence of 27 such organizations in the Muda area.

Furthermore, while we used an ordinary least-squares-based correlation to estimate the relationship between climate indices and rice yield, the current literature on weather index insurance suggests that quantile regression and copula approaches are more appropriate. Additionally, although historical burn analysis and index value modelling are common methods for pricing weather index insurance contracts, we only used the historical burn method. It is worth noting that our study only analysed spatial basis risk, whereas design basis risk and temporal basis risk issues also exist in weather index insurance.

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