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ORIGINAL ARTICLE

The effectiveness of weather index insurance in managing mariculture production risk

Mengmeng Qiang[1] | Manhong Shen[2] | Guanjun Xia[1]

[1]School of Economics and Management, Zhejiang Sci-Tech University, Hangzhou, 310018, China

[2]Institute of Ecological Civilization, Zhejiang A&F University, Hangzhou, 311300, China

Correspondence
Mengmeng Qiang, School of Economics and management, Zhejiang Sci-Tech University, Hangzhou 310018, China.
Email: qiangmmdyx@zstu.edu.cn

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Abstract
Mariculture is a high-risk industry that is susceptible to weather disasters. However, due to moral hazard, adverse selection and high transaction costs, traditional indemnity insurance policies are not available. An emerging alternative is the development of weather index mariculture insurance. This research assesses the effectiveness of weather index mariculture insurance by using the swimming crab precipitation index insurance as an example. The theoretical and empirical results suggest that weather index mariculture insurance is not always effective. It cannot be guaranteed to promote the welfare of mariculturists and reduce the tail risk of income, especially in the case of gross rates. However, in the case of low basis risk, it could be a viable option for the government because of the low subsidy cost required.

KEYWORDS
effectiveness, mariculture insurance, precipitation index, weather index insurance

JEL CLASSIFICATION
G22, Q14, Q22

1 | INTRODUCTION

With the shortage of fishery resources, many countries around the world have begun to regulate fishing and encourage mariculture (Salayo et al., 2012). The healthy development of mariculture is critical for alleviating the shortage of fishery resources, ensuring food security and enhancing populations' nutritional status (Delgado, 2003). However, mariculture is a high-risk industry that is vulnerable to weather disasters (Ahsan & Roth, 2010; Bergfjord, 2009; Joffre et al., 2018; Le & Cheong, 2010). In response to weather risks, many countries have launched mariculture insurance projects. However, due to moral hazard, adverse selection and high transaction costs, the failure of traditional mariculture insurance has been widespread in many countries (Hotta, 1999; Van Anrooy et al., 2006; Yuan et al., 2017).

An emerging alternative is the development of weather index mariculture insurance (Roberts, 2007). Weather index insurance for aquatic products such as swimming crab, laver and sea cucumber has been piloted in practice. As opposed to traditional insurance, the indemnity of weather index insurance is determined by a weather index that is closely related to the loss instead of the actual loss (Carter et al., 2017; Miranda & Farrin, 2012). Weather data are collected from a weather station, which is transparent and difficult to manipulate. Therefore, there is no moral hazard or adverse selection. Moreover, insurers simply need to determine the loss based on weather data, reducing transaction costs (Barnett et al., 2008; Collier et al., 2009; Fuchs & Wolff, 2011; Skees, 2008).

However, the imperfect correlation between the weather index and mariculture yield, the so-called basis risk, constitutes a weakness of weather index mariculture insurance. Basis risk comes from two aspects. The index cannot accurately predict the mariculture yield and may not capture the weather experienced by mariculturists (Norton et al., 2013). Weather index insurance performance has been considerably weakened by basis risk (Carter et al., 2016; Clarke, 2016; Jensen et al., 2018, 2019). Therefore, whether weather index insurance can effectively protect mariculture production needs careful evaluation.

As an emerging financial product, weather index insurance has attracted the extensive attention of scholars (Barnett & Mahul, 2007; Hill et al., 2013; Jensen & Barrett, 2017). Several studies have investigated the effectiveness of weather index insurance in managing crop and livestock risks. Leblois et al. (2014) show that the potential of precipitation index insurance is limited, and the benefit is only slightly higher than the cost. However, some studies have found that weather index insurance can significantly improve farmers' welfare. For example, Martin et al. (2001) showed that precipitation index insurance in Mississippi significantly improved farmers' livelihoods. Other scholars also found that weather index insurance had a protective effect on crop production (Conradt et al., 2015; Deng et al., 2007; Turvey, 2001; Ye et al., 2017). Vedenov and Barnett (2004) argue that weather index insurance has different performances for various crops.

The aim of this paper was to investigate the effectiveness of weather index insurance in managing mariculture risks. We take swimming crab precipitation index insurance, a typical weather index mariculture insurance product, as an example for empirical analysis. The growth of swimming crabs is vulnerable to precipitation disasters (Lu et al., 2019), as heavy rain will change the salinity of the aquaculture pond. Aquatic experiments have shown that appropriate salinity is the key to the growth of swimming crabs, and a low-salinity environment will reduce the respiration, metabolism and immunity of swimming crabs. A sharp drop in salinity will lead to the death of swimming crabs (Romano & Zeng, 2006; Wang et al., 2018). Note that the effectiveness assessment should not rely on an existing weather index insurance contract, as it might not be well designed. Therefore, this study consists of two parts: (1) designing a technically sound swimming crab precipitation index insurance product and (2) evaluating its effectiveness.

This paper extends and improves upon the literature in three important aspects. Firstly, most studies have focussed on crop and livestock index insurance products (Chantarat et al., 2017; Leblois et al., 2014; Shirsath et al., 2019). To the best of our knowledge, this is the first study to quantify the benefit of weather index mariculture insurance.

Secondly, previous studies have mainly analysed the effectiveness of weather index insurance from the perspective of farmers' welfare (Bucheli et al., 2021, 2022; Conradt et al., 2015; Leblois et al., 2014). However, this could neglect the advantage of the low subsidy cost of weather index insurance. Although premium subsidies have long been controversial (Coble & Barnett, 2013; Goodwin & Smith, 2013; Möhring et al., 2020), they are very common in agricultural insurance as a green-box tool. In practice, the government typically subsidises premiums for mariculture insurance. Hence, when premium subsidies are unavoidable, weather index mariculture insurance is still viable for the government as long as the subsidy cost is lower than that of traditional indemnity insurance. Therefore, this paper not only focusses on the welfare effect of weather index mariculture insurance but also considers its government subsidy cost.

Thirdly, the previous discussions on the effectiveness of weather index insurance are mostly based on empirical results (Chantarat et al., 2007; Deng et al., 2007; Zant, 2008). This paper provides a theoretical analysis, which ensures the generalisability of the findings. This research reveals that the efficiency of weather index mariculture insurance is ambiguous, depending on mariculturists' characteristics and insurance parameters. It cannot be guaranteed to promote the welfare of mariculturists, especially in the case of gross rates. However, in the case of low basis risk, the subsidy cost of weather index mariculture insurance is lower than that of traditional indemnity insurance.

The remainder of the article is organised as follows. The second section provides a theoretical analysis. The third section introduces the study area and data. The fourth section presents the methods for the design and effectiveness evaluation of precipitation index insurance. The fifth section reports the empirical results. The sixth section discusses the findings and concludes the article.

2 | THEORETICAL MODEL

In this section, we develop a theoretical model that allows for the analysis of the effectiveness of weather index mariculture insurance. It is assumed that the representative mariculturist is risk averse and has initial wealth w. Production is exposed to a weather disaster with probability p. When a weather disaster occurs in the region, the probability of loss l is q_a. In the absence of a weather disaster in the region, the probability of loss l is q_b. Basis risk can be determined by q_a and q_b. Lower basis risk is indicated by a larger q_a and a smaller q_b. When $q_a = 1$ and $q_b = 0$, there is no basis risk. Mariculturists can buy an index insurance product with an indemnity I and a premium rate π to hedge the risk. The indemnity fully covers the loss, that is, $I = l$.

Consider the supply of insurance. It is assumed that the market is competitive and the expected profit of insurance companies is zero.

$$(1-p)\pi l + p(\pi l - l) - \kappa \pi l = 0 \tag{1}$$

where κ is the premium load and $\kappa\pi l$ represents the management costs of insurance companies. The zero-profit condition is the premium rate $\pi = \frac{p}{1-\kappa}$. For convenience, we denote $m = \frac{1}{1-\kappa}$.

Then, consider the demand for index insurance. Mariculturists face four states: (1) weather disaster and loss; (2) weather disaster and no loss; (3) no weather disaster and loss; and (4) no weather disaster and no loss. The income of mariculturists in the four states is shown in Table 1. The expected utility of mariculturists can be written as:

$$\begin{aligned} EU_1 = \; & pq_a U(w-mpl) + p\left(1-q_a\right) U(w-mpl+l) + \\ & (1-p)q_b U(w-mpl-l) + (1-p)\left(1-q_b\right) U(w-mpl) \end{aligned} \tag{2}$$

$$EU_2 = \left[pq_a + (1-p)q_b\right] U(w-l) + \left[1 - pq_a - (1-p)q_b\right] U(w) \tag{3}$$

TABLE 1 Income of mariculturists in four states.

State	Loss	No loss
Weather disaster	$w - mpl$	$w - mpl + l$
No weather disaster	$w - mpl - l$	$w - mpl$

where EU_1 and EU_2 represent expected utility with and without index insurance, respectively.

Denote $\Delta = EU_1 - EU_2$ as the change in utility. Note that the premium rate π is the lowest level acceptable to the insurance company. Moreover, there is no design error in the weather index insurance product. In this case, Δ represents the maximum welfare effect of the weather index insurance product with a given basis risk. Δ depends on parameters p, w, l, m, q_a and q_b and the risk aversion coefficient γ.

For various parameter values, Δ could be larger than or less than zero. This judgement can be illustrated by changes in two variables: basis risk and premium load. When mariculturists are risk averse, their utility functions are concave (i.e. $U'(\cdot) > 0$ and $U''(\cdot) < 0$). In this case, the comparative statics analysis shows the following:

$$\frac{\partial \Delta}{\partial q_a} = p\left[U(w) + U(w - mpl) - U(w - l) - U(w - mpl + l)\right] > 0 \tag{4}$$

$$\frac{\partial \Delta}{\partial q_b} = (1 - p)\left[U(w) - U(w - mpl) - U(w - l) + U(w - mpl - l)\right] < 0 \tag{5}$$

$$\frac{\partial \Delta}{\partial \kappa} = -\frac{pl}{(1-\kappa)^2}\left[\begin{array}{c} pq_a U'(w-mpl)+p\left(1-q_a\right)U'(w-mpl+l)+ \\ (1-p)q_b U'(w-mpl-l)+(1-p)\left(1-q_b\right)U'(w-mpl) \end{array}\right] < 0 \tag{6}$$

These results suggest that the welfare of weather index mariculture insurance is negatively correlated with the basis risk and premium load. We consider an ideal situation in which there is no basis risk and premium load, that is, $q_a = 1$, $q_b = 0$, and $\kappa = 0$. In this case, $\Delta$is always greater than zero.

$$\begin{aligned} \Delta &= U(w-pl)-pU(w-l)-(1-p)U(w) \\ &= U\left[p(w-l)+(1-p)w\right]-pU(w-l)-(1-p)U(w)>0 \end{aligned} \tag{7}$$

Therefore, it can be inferred that when the premium load and basis risk are small, weather index mariculture insurance can improve welfare. Conversely, when these two parameters become large, index insurance will be inefficient, and premium subsidies will be needed.

> **Proposition 1.** The weather index mariculture insurance cannot be guaranteed to improve the welfare of mariculturists, especially in the case of high basis risk and gross rates.

We then compare the government subsidy costs for different insurance products. Denote s^w and s^t as the government subsidy ratio for weather index insurance and traditional indemnity insurance, respectively. n is the premium load in traditional indemnity insurance. According to the model, the subsidy ratio is determined by the following equation:

$$s^w = f\left(p, w, l, \gamma, \kappa, q_a, q_b\right) \tag{8}$$

$$s^t = f(p, w, l, \gamma, n) \tag{9}$$

The difference lies in two parameters: basis risk and premium load. Due to the serious failure of traditional indemnity insurance policies, n is greater than κ. Therefore, according to the comparative statics analysis above, in the case of low basis risk, $s^w < s^t$:

Proposition 2. *In the case of low basis risk, the subsidy ratio required by weather index mariculture insurance is less than that of traditional indemnity insurance.*

3 | STUDY AREA AND DATA

3.1 | Study area

The empirical analysis focusses on swimming crab precipitation index insurance in China. China is the largest mariculture country in the world, accounting for approximately 60% of the world's annual yield. The swimming crab is an important mariculture species in China and is distributed in Jiangsu, Fujian, Zhejiang, Shandong and Guangdong provinces. Swimming crabs account for approximately 8% of China's mariculture areas and are the largest crab aquatic product. Insurance products for swimming crabs are common and typical.

This paper chooses Xiangshan County, Hanjiang County and Licheng County as the research areas. Their mariculture is developed, and weather index mariculture insurance has been piloted. Yield data are available for the three counties. Xiangshan County is located in Ningbo City, Zhejiang Province, while Hanjiang County and Licheng County are located in Putian City, Fujian Province. All three counties belong to the subtropical maritime monsoon climate zone, with frequent typhoon activity. Figure 1 shows the locations of the three counties.

In response to weather risks, the three counties have launched weather index insurance for swimming crab, white shrimp, laver, and other varieties. The Fishery Mutual Insurance Association and the People's Insurance Company of China (PICC) are their main underwriting institutions.

3.2 | Yield data

The empirical analysis uses two sets of data: yield data and climate data. Yield data are collected from the Bureau of Fisheries for each county. Ideally, the performance of swimming crab precipitation index insurance should be based on the historical yield of mariculturists. Unfortunately, such data are not available. Consequently, county-level data from different periods are employed to conduct the performance analysis. This is a widely used approach to assess the benefits of weather index insurance, especially in the absence of farm-level data (Vedenov & Barnett, 2004; Ye et al., 2017).

As shown in Table 2, the mean yield of swimming crabs in Putian City was higher than that in Ningbo City. The maximum yield in the three counties was 3507.04 kg/ha, and the minimum yield was 1157.10 kg/ha. The standard deviation of yield in the three counties is relatively small, and the yield trend is stable. Therefore, the empirical analysis can be based on actual yields.

3.3 | Weather data

The weather data are collected from the China Meteorological Data Sharing Service Center. The data for Xiangshan County come from the Shipu Weather Station (no. 58569). It was built in 1955 and is the most accurate observation station for weather data in Xiangshan County. However, weather stations are not widely distributed in Putian City, and there are none in the territory of Hanjiang and Licheng Counties. To minimise spatial basis risk, weather data from the Xianyou weather station (no. 58936) are utilised to develop corresponding index insurance products. The Xianyou weather station was established in 1956, adjacent to Hanjiang County and Licheng County, and can well capture the weather of the two counties.

FIGURE 1 Location of the study area. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Summary statistics of swimming crab yields of case study counties (kg/ha).

City	County	Period	Mean	SD	Min	Max
Putian	Hanjiang	2009–2017	2615.11	380.85	2228.07	3183.91
Putian	Licheng	2009–2017	2981.62	292.28	2641.03	3507.04
Ningbo	Xiangshan	2000–2018	1568.02	296.42	1157.10	2294.62

Note: SD is the standard deviation.

Table 3 shows the precipitation during the growth period of swimming crabs (from July to October). The maximum precipitation at the Xianyou weather station is 212.4 mm, while that at the Shipu weather station is 286.7 mm.

4 | METHODS

4.1 | Design and pricing of precipitation index insurance

4.1.1 | Insurance period and precipitation index

The culture of swimming crabs is divided into two stages: the seedling period (February–June) and the growth period (July–October). Because the uncertainty of the seedling period

TABLE 3 Summary statistics of daily precipitation from July to October at two stations (mm).

	Xianyou weather station, 2009–2017				Shipu weather station, 2000–2018			
Month	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
July	7.00	21.22	0.00	212.40	3.36	11.81	0.00	159.50
August	7.09	14.87	0.00	109.90	5.66	14.42	0.00	118.90
September	6.59	21.99	0.00	185.20	6.47	19.00	0.00	239.60
October	1.73	7.33	0.00	62.40	3.04	16.13	0.00	286.70

is large, insurance companies will not underwrite. Therefore, the protection period of swimming crab precipitation index insurance is from July to October. In addition, there are different indices for precipitation index insurance, such as the number of heavy rains, cumulative rainfall, the weighted average of cumulative rainfall and other complex indices (Leblois et al., 2014). The most common daily precipitation in practice is adopted in this paper.

4.1.2 | Indemnity schedule

Referring to previous literature (Turvey, 2001; Vedenov & Barnett, 2004), the indemnity is a stepwise linear function of the precipitation index.

$$indemnity_i = \psi \times liability \times \theta_{month} \times \begin{cases} 0 & x_i < x_{strike} \\ \dfrac{x_i - x_{strike}}{x_{limit} - x_{strike}} & x_{limit} > x_i \geq x_{strike} \\ 1 & x_i \geq x_{limit} \end{cases} \tag{10}$$

where $indemnity_i$ is the indemnity for day i. ψ is the maximum loss rate caused by precipitation disasters. θ_{month} is the indemnity proportion in different growth months. Mariculturists have various breeding costs in different months, which correspond to varied indemnity proportions. *liability* is the insurance liability, which represents the total insured value. x_i is the precipitation index realisation on day i. x_{strike} and x_{limit} are the index strike and limit, respectively. The index strike means the observed weather index level at which the insured becomes eligible for claim payment. The index limit refers to the observed weather index level at which the indemnity reaches its maximum. A schematic diagram of the indemnity is shown in Figure 2.

Referring to the insurance practice of the PICC, the liability is set at 9300.16 USD/ha, determined by the breeding cost. ψ is set at 35%. The indemnity proportion in different growth months is shown in Table 4.

4.1.3 | Insurance pricing

The gross premium rates of insurance can be decomposed into three components in the form of $\delta = r + \lambda + \xi$, including the actuarially fair premium rates r, the catastrophe buffer load λ, and the administrative cost load ξ (Holly Wang & Zhang, 2003; Ye et al., 2020). The pricing of actuarially fair premium rates follows the principle of cost–benefit equivalence. Assuming that the probability density function of the precipitation index is $f(x)$, the actuarially fair rate is:

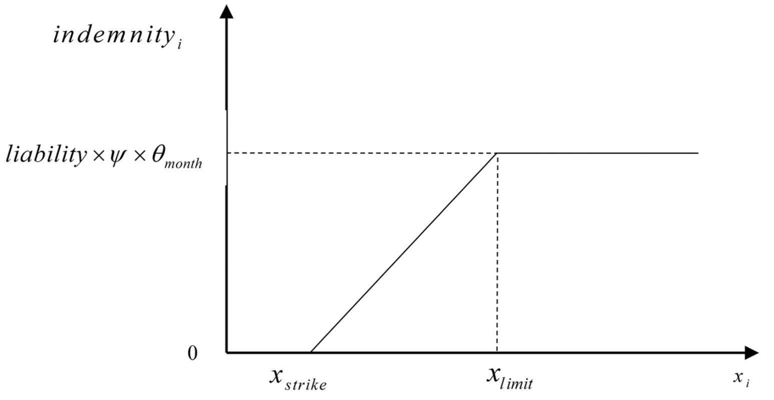

FIGURE 2 Schematic diagram of the indemnity schedule.

TABLE 4 θ_{month} in different growth months.

Month	θ_{month}
July	15%
August	25%
September	35%
October	40%

$$r = \frac{E(indemnity_i)}{liability} = \psi \times \sum_{month=July}^{October} (T_{month} \times \theta_{month}) \times \left[\int_{x_{strike}}^{x_{limit}} \left(\frac{x_i - x_{strike}}{x_{limit} - x_{strike}} \right) f(x_i) dx_i + \int_{x_{limit}}^{\infty} f(x_i) dx_i \right]$$
$$= 35\% \times (31 \times 15\% + 31 \times 25\% + 30 \times 35\% + 31 \times 40\%) \times \left[\int_{x_{strike}}^{x_{limit}} \left(\frac{x_i - x_{strike}}{x_{limit} - x_{strike}} \right) f(x_i) dx_i + \int_{x_{limit}}^{\infty} f(x_i) dx_i \right] \quad (11)$$

where $E(indemnity_i)$ is the expected indemnity for the whole insurance period. T_{month} is the number of days in each month.

Informed by previous studies (Ozaki et al., 2008; Sherrick et al., 2004), the probability density function of the precipitation index is selected in alternative distributions according to Anderson–Darling statistics. Specific alternative distributions include normal, log-normal, logistic, beta, Burr, gamma, Weibull, log-logistic, Johnson SB, Frechet, Pearson 5 and Pearson 6.

According to the practice of the PICC, the catastrophe buffer load λ is set at 10% of the gross rate δ. In addition, because the indemnity of weather index insurance is convenient and there is almost no administrative cost, ξ is set at zero. Finally, combined with the equation $\delta = r + \lambda + \xi$, the gross rate is:

$$\delta = \frac{r}{1 - 10\%} = 1.11 \times r \quad (12)$$

4.1.4 | Parameter optimisation

Finally, we need to determine the two most important parameters: the index strike and limit. The literature provides different parameter optimisation methods, such as judgement based on agronomic knowledge (Ye et al., 2017), quantile regression (Bucheli et al., 2021, 2022; Dalhaus & Finger, 2016; Vroege et al., 2021), minimising downside loss (Vedenov & Barnett, 2004) and maximising the welfare of farmers (Deng et al., 2007; Leblois et al., 2014; Mahul, 2001). This paper optimises insurance parameters by maximising the utility of mariculturists, as this can test the maximum potential of weather index mariculture insurance to improve welfare. This is consistent with the theoretical model.

The specific principle is as follows. Assuming that the yield in year t is y_t and the price of swimming crab is *price* (without loss of generality, we set the price of swimming crab at 7.75 USD/kg), the income R_t is:

$$\begin{aligned} R_t &= price \times y_t - premium_t + indemnity_t \\ &= price \times y_t - \delta\left(x_{strike}, x_{limit}\right) \times liability + \sum_{i=1}^{123}\left[indemnity\left(x_i\right)\right] \end{aligned} \tag{13}$$

where $premium_t$ and $indemnity_t$ are the premium and indemnity in year t, respectively. $indemnity_t$ is the sum of daily indemnity for 123 days of the insurance period. It is assumed that the preferences of mariculturists follow the constant relative risk aversion (CRRA) utility function. The utility of mariculturists in year t is:

$$\begin{cases} U\left(R_t\right) = \dfrac{\left(R_t\right)^{1-\gamma}}{1-\gamma}, & \gamma \neq 1 \\ U\left(R_t\right) = \ln\left(R_t\right), & \gamma = 1 \end{cases} \tag{14}$$

where $U(\cdot)$ is the utility and γ is the risk aversion coefficient. Ye and Wang (2013) show that the risk aversion coefficient of Chinese farmers ranges from 0.81 to 1.32, and they set it as 1 in their empirical analysis. Considering the higher income level and production risk, this paper assumes that the risk aversion coefficient of mariculturists is slightly higher than that of farmers, and it is set at 1.1. The certainty equivalent revenue (CER) corresponds to:

$$\begin{cases} EU\left(R_t\right) = \dfrac{(CER)^{1-\gamma}}{1-\gamma} \\ CER = \left[(1-\gamma)EU\left(R_t\right)\right]^{\frac{1}{1-\gamma}} \end{cases} \tag{15}$$

Combined with Equation (4), the optimal index parameter can be obtained by maximising the CER.

4.2 | Decision criteria for the effectiveness of index insurance

For mariculturists, aquaculture is the main source of income. Severe weather disasters can even impoverish mariculturists. The function of insurance is to reduce risk and stabilise income. Effective swimming crab precipitation index insurance should play two roles: improving the overall welfare of mariculturists and reducing the tail risk of income.

The welfare improvement effect of index insurance can be judged by comparing the CERs of mariculturists in different conditions. Effective insurance should ensure that the CER with insurance is not less than the CER without insurance, that is:

$$\Delta CER = CER\left(R_t\right) - CER\left(R_t^{net}\right) \geq 0 \tag{16}$$

where $R_t^{net} = price \times y_t$ represents the revenue of mariculturists without insurance.

Value-at-risk (VaR) is employed to analyse the potential of index insurance to reduce the tail risk of income. Despite its origins in the field of financial investment, VaR is essentially an indicator to measure downside risk. Therefore, it has applicability in other fields, such as agriculture risk (Manfredo & Leuthold, 1999). Some scholars have employed the VaR method to evaluate the performance of agricultural weather index insurance (Breustedt et al., 2008; Deng et al., 2007; Shi & Jiang, 2016; Vedenov & Barnett, 2004). The formula is:

$$\Pr\left(R_t < VaR_\alpha\right) = \alpha \tag{17}$$

where α is the given probability and informed by the previous literature (Deng et al., 2007), 2.5%, 5% and 10% are selected in this study. It refers to the maximum income of mariculturists under a given probability level α in this paper. Higher values of VaR correspond to lower risk exposures. Effective index insurance requires that $VaR_\alpha\left(R_t\right)$ with insurance is greater than $VaR_\alpha\left(R_t^{net}\right)$ without insurance:

$$VaR_\alpha\left(R_t\right) \geq VaR_\alpha\left(R_t^{net}\right) \tag{18}$$

5 | RESULTS

5.1 | Optimal insurance parameters

Figures 3 and 4 show the daily precipitation distribution at two weather stations. In the previous literature (Deng et al., 2007), the maximum value of the sample is generally selected as the index limit. However, according to the sample characteristics, it could be inappropriate because the possibility of precipitation approaching the maximum value is extremely low. This will not only raise the premium rate but also reduce the likelihood of indemnity. We finally set the index limit at 135 mm, which is greater than most of the precipitation, and the probability of compensation for mariculturists is not low. By comparing the Anderson–Darling statistics of different alternative distributions, it is determined that the distributions of the daily precipitation at two weather stations both follow the Gamma function, which is consistent with the existing studies (Martin et al., 2001).

Based on the index limit and the probability density function of the daily precipitation, this paper calculates the CERs of mariculturists under different index strikes. The optimal index strikes for insurance contracts are found to be 87 mm, 77 mm and 81 mm for Xiangshan, Hanjiang and Licheng, respectively. These are the index strikes that yield the largest CER. According to the insurance pricing equation, the parameters of swimming crab precipitation index insurance are shown in Table 5. The actuarially fair rates of the precipitation index insurance in the three counties are 5.32%, 7.96% and 7.45%, respectively; the gross rates are 5.91%, 8.83% and 8.27%, respectively.

5.2 | Effectiveness evaluation

Based on the insurance parameters, this paper calculates the annual income of three counties under different insurance situations and evaluates the performance of index insurance.

Table 6 presents changes in mariculturists' well-being from purchasing index insurance as measured by CER. The results were presented under two scenarios: actuarially fair rates and gross rates. The performance of precipitation index insurance varies greatly. In the case of actuarially fair rates, precipitation index insurance in Xiangshan County shows a good welfare improvement effect, but the other two counties experience the opposite effect. This disparity

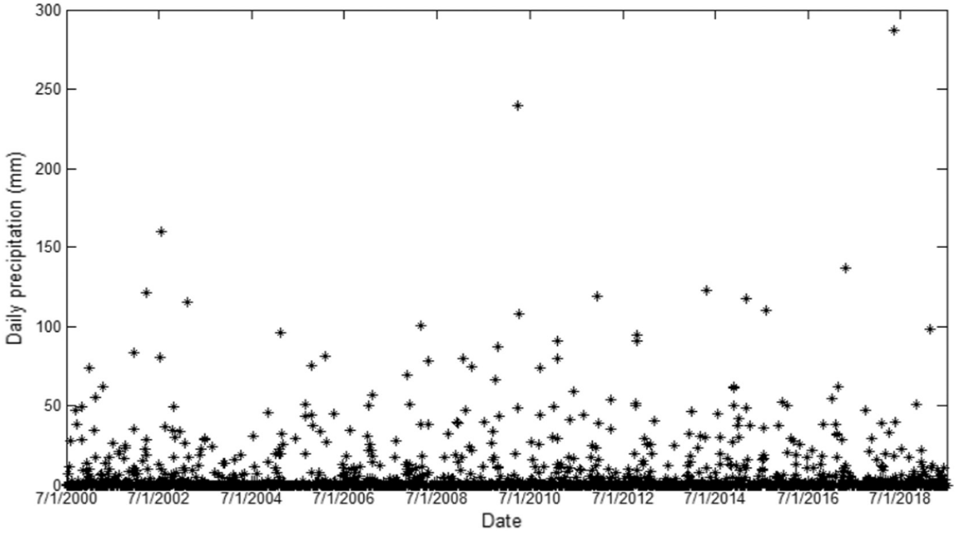

FIGURE 3 Distribution of daily precipitation at the Shipu weather station from July to October.

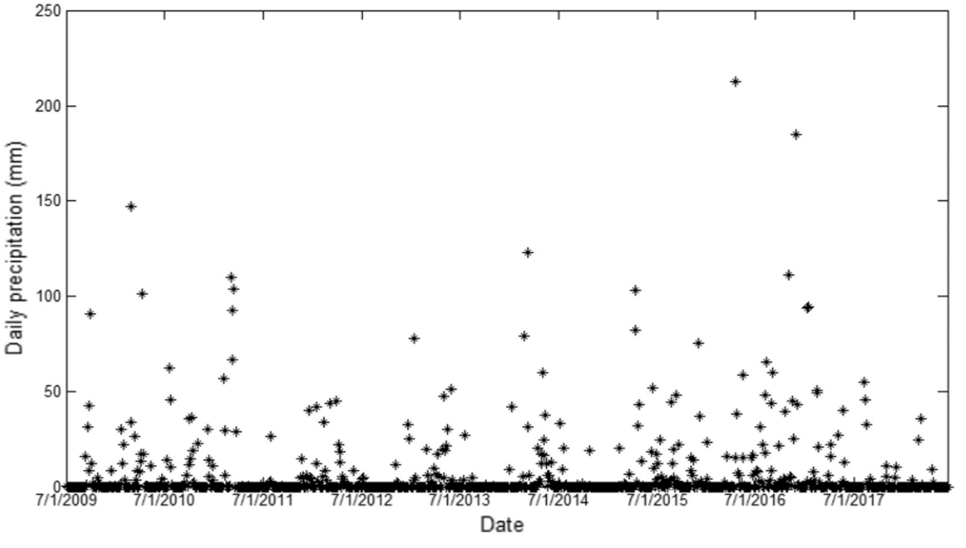

FIGURE 4 Distribution of daily precipitation at the Xianyou weather station from July to October.

could be due to spatial basis risk, in which the climate of Hanjiang and Licheng counties is not perfectly captured by the Xianyou weather observation station. The weather station is only adjacent to the two counties, not within their territories. Moreover, it can be inferred that the spatial basis risk of index insurance in Licheng is high because CER loss is large. In the case of gross rates, swimming crab precipitation index insurance products in the three counties all failed to increase the CERs of mariculturists. If there is no government subsidy, mariculturists will not participate in weather index mariculture insurance.

The results are consistent with the performance of swimming crab precipitation index insurance in practice. In the case of gross rates, actual insurance products are not in great demand without government subsidies. To promote the take-up of index insurance, the governments

TABLE 5 Parameters of the swimming crab precipitation index insurance products.

Insurance parameters	Xiangshan	Hanjiang	Licheng
x_{strike} (mm)	87	77	81
x_{limit} (mm)	135	135	135
Actuarially fair premium rate r	5.32%	7.96%	7.45%
Gross premium rate δ	5.91%	8.83%	8.27%
Liability (USD/ha)	9300.16	9300.16	9300.16
Premium (USD/ha)	549.64	821.20	769.12

TABLE 6 Effectiveness of index insurance as measured by CER (USD/ha).

	CER		
Premium structure	Xiangshan	Hanjiang	Licheng
Without insurance	23878.50	40132.83	46006.88
Actuarially fair rate	23905.23	40132.41	45964.94
Gross rate	23849.85	40050.24	45888.35

of three counties subsidised premiums. According to the operating data of PICC in 2018, with government subsidies, the total premium of swimming crab precipitation index insurance increased by 143% year on year, and the loss ratio of the insurance company was 68%, which means it has achieved good sustainability.

The efficiency analysis based on the VaR measure is shown in Table 7. The VaR with insurance in Xiangshan County and Hanjiang County is always greater than the VaR without insurance. Even in the case of gross rates, the two index insurance products significantly reduce the tail risk of income. However, because of the high spatial basis risk, index insurance in Licheng County displays no such effect.

In summary, weather index mariculture insurance partially shows a welfare improvement effect and the ability to reduce the tail risk of income, but these performances are not constant. This suggests that weather index mariculture insurance has a certain potential, but it is not perfect.

5.3 | Out-of-sample performance of index insurance

In the previous section, we optimised the insurance parameters and then evaluated the performance with the same data. This is referred to as the in-sample result. However, in actual insurance implementation, the design of index insurance is based on historical data, but the performance depends on the future situation. Hence, we need to run an out-of-sample analysis to test the performance of index insurance (Vedenov & Barnett, 2004). Because the data periods of Hanjiang County and Licheng County are too short for an out-of-sample analysis, this section only uses Xiangshan County as an example. The sample is divided into two periods: 2000–2009 and 2010–2018. The first subset is used to calibrate insurance parameters, and the second subset is used to evaluate the out-of-sample performance of the designed insurance product.

Tables 8 and 9 present the out-of-sample performance of the index insurance as measured by CER and VaR. In the case of actuarially fair rates, precipitation index insurance still effectively reduces the tail risk of income and improves welfare. In contrast, in the case of gross rates, swimming crab precipitation index insurance increases the CERs of mariculturists.

TABLE 7 Effectiveness of index insurance as measured by VaR (USD/ha).

County	VaR	With insurance		Without insurance
		Actuarially fair rate	Gross rate	
Xiangshan	$VaR_{0.025}$	17957.22	17902.58	17445.01
	$VaR_{0.05}$	18498.72	18444.08	18101.37
	$VaR_{0.10}$	19254.82	19200.42	18996.74
Hanjiang	$VaR_{0.025}$	35029.99	34948.38	34112.76
	$VaR_{0.05}$	35129.74	35048.13	34431.06
	$VaR_{0.10}$	35294.82	35213.44	34890.72
Licheng	$VaR_{0.025}$	40074.63	39999.77	40576.61
	$VaR_{0.05}$	40427.57	40351.78	41081.61
	$VaR_{0.10}$	40978.84	40903.05	41671.47

This highlights the fact that in-sample performance is not exactly equivalent to out-of-sample performance. This phenomenon has been observed in the literature (Berg et al., 2009; Leblois et al., 2014; Vedenov & Barnett, 2004). However, this creates the risk that insurance designed based on in-sample data may not always work perfectly in practice. This also suggests that the performance of weather index mariculture insurance is ambiguous.

5.4 | Government subsidy costs of index insurance

In the in-sample estimation (as shown in Table 6), we found that the swimming crab precipitation index insurance reduced the CERs of mariculturists in the case of gross rates. For mariculturists to buy insurance, the government needs premium subsidies. This creates the question of how much the government should subsidise. Weather index mariculture insurance is still a viable alternative for the government if the subsidy cost is not too high.

Assuming that the premium subsidy ratio is s^w, then the income of mariculturists with index insurance in year t is:

$$R_t = price \times y_t - (1 - s^w) \times \delta\left(x_{strike}, x_{limit}\right) \times liability + \sum_{i=1}^{123} \left[indemnity\left(x_i\right)\right] \tag{19}$$

The minimum government subsidy ratio s^{w*} corresponds to the case of $\Delta CER = 0$. The minimum subsidy cost E of weather index insurance is:

$$E = 9300.16 \times \delta \times s^{w*} \tag{20}$$

Figure 5 shows the minimum subsidy ratio required for index insurance in the three counties. The $\Delta CERs$ of the three counties equal zero when the subsidy rates are 5%, 10% and

TABLE 8 Out-of-sample performance of index insurance as measured by CER (USD/ha).

County	Premium structure	CER
Xiangshan	Without insurance	22882.93
	Actuarially fair rate	23031.25
	Gross rate	22954.08

TABLE 9 Out-of-sample performance of index insurance as measured by VaR (USD/ha).

County	VaR	With insurance		Without insurance
		Actuarially fair rate	Gross rate	
Xiangshan	$VaR_{0.025}$	15829.81	15753.31	15138.34
	$VaR_{0.05}$	16991.86	16915.37	16411.30
	$VaR_{0.10}$	18357.36	18281.10	17901.42

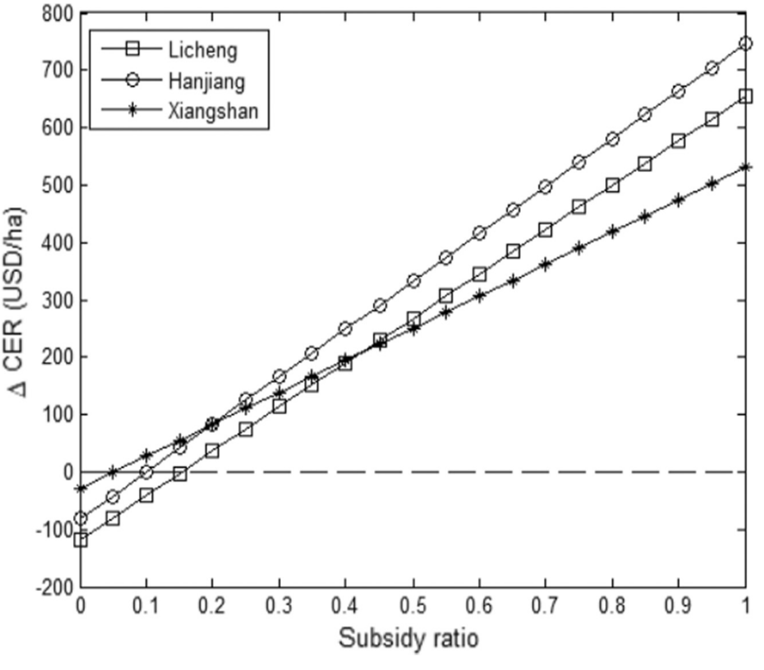

FIGURE 5 CER changes of mariculturists under different subsidy ratios.

15%. The corresponding government subsidy costs are 27.48 USD/ha, 81.12 USD/ha and 115.37 USD/ha, respectively. In comparison, the subsidy cost of index insurance is significantly lower than that of traditional indemnity insurance. In reality, more than 50% of mariculture indemnity insurance premiums are routinely covered by the government. In light of this, even though weather index mariculture insurance is not perfect, it is still an option worth considering.

In summary, the empirical analysis supports the two propositions of this paper. The efficiency of weather index mariculture insurance is ambiguous. In the case of low basis risk, the requisite government subsidy ratio of weather index mariculture insurance is not high.

6 | DISCUSSION AND CONCLUSION

6.1 | Key findings

This paper discusses the effectiveness of weather index insurance in managing mariculture production risk by using swimming crab precipitation index insurance as an example. Two key findings are highlighted.

On the one hand, despite having the potential to protect mariculture production, weather index insurance is not perfect. The results show that the performance of different precipitation index insurance products varies greatly. It is not guaranteed to promote the welfare of mariculturists and reduce the tail risk of income, especially in the case of gross rates. This is inconsistent with the findings of some scholars. For example, Ye et al. (2017) demonstrated that even when the loading for administrative costs is included in the premium, snow index insurance could still effectively manage livestock mortality risk. Deng et al. (2007) suggested that even if the premium were higher than the actuarially fair level and the spatial and temporal basis risks were considered, temperature–humidity insurance could still benefit dairy producers. Our results are similar to the findings of Leblois et al. (2014) and Vedenov and Barnett (2004). They also found that weather index insurance was not always efficient in managing crop production risk. Indeed, our theoretical analysis shows that the efficiency of weather index mariculture insurance is ambiguous. It depends on various parameters, such as basis risk, wealth, production risk, risk aversion and premium load.

On the other hand, weather index mariculture insurance is superior to indemnity insurance in the case of low basis risk because it requires a low premium subsidy cost. Previous literature has mostly evaluated the efficiency of weather index insurance from the perspective of farmers' welfare (Berg et al., 2009; Martin et al., 2001) and ignored its impact on government subsidy costs. The results show that when the basis risk is not high, the government cost of weather index insurance is much lower than that of traditional indemnity insurance. This reflects the advantage of lower administrative costs of weather index insurance (Skees, 2008; Skees & Barnett, 2006).

Therefore, our final conclusion is positive: although weather index mariculture insurance is not perfect, it is still a viable option due to the low subsidy cost required when the indemnity structure is well designed.

6.2 | Policy implications

The findings suggest that weather index mariculture insurance should be promoted. When traditional indemnity insurance fails, weather index mariculture insurance is a cost-effective choice. With policy support from the government, weather index mariculture insurance can be an effective risk management tool. However, it is necessary to develop corresponding index products according to the leading weather hazards of different mariculture varieties. An appropriate weather index can effectively reduce basis risk.

However, attention should be devoted to the efficiency of weather index mariculture insurance. Although such insurance has potential, empirical analysis has revealed that insurance design has a substantial impact on the quality of insurance products. The government needs to strengthen its effectiveness evaluation. Furthermore, the satisfaction of mariculturists with insurance products should be investigated because the in-sample performance may be inconsistent with the out-of-sample performance.

6.3 | Future research

This paper only discusses swimming crab precipitation index insurance, and future research can also focus on wind index, temperature index and other index insurance products. In practice, some areas have developed index insurance bundled with a variety of weather hazards, and scholars could study the design and pricing of such insurance.

In addition, this paper evaluates the effectiveness of weather index insurance from the perspective of the mariculturist and the government. Future studies could be conducted from the perspective of basis risk.

Further, the empirical analysis in this paper is based on county-level data. Future research could use farm-level data to assess the feasibility of weather index mariculture insurance. This would allow for a more precise assessment of the influence of weather index mariculture insurance on various mariculturists.

Finally, the theoretical model in this paper could be further expanded. This paper only conducts a comparative static analysis of basis risk and premium load. Future research could analyse the effects of other parameters on welfare changes. This could clarify the circumstances in which premium subsidies are beneficial.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID
Mengmeng Qiang https://orcid.org/0000-0002-7173-0508

REFERENCES

Ahsan, D.A. & Roth, E. (2010) Farmers' perceived risks and risk management strategies in an emerging mussel aquaculture industry in Denmark. *Marine Resource Economics*, 25, 309–323.

Barnett, B.J., Barrett, C.B. & Skees, J.R. (2008) Poverty traps and index-based risk transfer products. *World Development*, 36, 1766–1785.

Barnett, B.J. & Mahul, O. (2007) Weather index insurance for agriculture and rural areas in lower-income countries. *American Journal of Agricultural Economics*, 89, 1241–1247.

Berg, A., Quirion, P. & Sultan, B. (2009) Can weather index drought insurance benefit to least developed Countries' farmers? A Case Study on Burkina Faso. *Weather, Climate and Society*, 1, 71–84.

Bergfjord, O.J. (2009) Risk perception and risk management in Norwegian aquaculture. *Journal of Risk Research*, 12, 91–104.

Breustedt, G., Bokusheva, R. & Heidelbach, O. (2008) Evaluating the potential of index insurance schemes to reduce crop yield risk in an arid region. *Journal of Agricultural Economics*, 59, 312–328.

Bucheli, J., Dalhaus, T. & Finger, R. (2021) The optimal drought index for designing weather index insurance. *European Review of Agricultural Economics*, 48, 573–597.

Bucheli, J., Dalhaus, T. & Finger, R. (2022) Temperature effects on crop yields in heat index insurance. *Food Policy*, 107, 102214.

Carter, M., de Janvry, A., Sadoulet, E. & Sarris, A. (2017) Index insurance for developing country agriculture: a reassessment. *Annual Review of Resource Economics*, 9, 421–438.

Carter, M.R., Cheng, L. & Sarris, A. (2016) Where and how index insurance can boost the adoption of improved agricultural technologies. *Journal of Development Economics*, 118, 59–71.

Chantarat, S., Barrett, C.B., Mude, A.G. & Turvey, C.G. (2007) Using weather index insurance to improve drought response for famine prevention. *American Journal of Agricultural Economics*, 89, 1262–1268.

Chantarat, S., Mude, A.G., Barrett, C.B. & Turvey, C.G. (2017) Welfare impacts of index insurance in the presence of a poverty trap. *World Development*, 94, 119–138.

Clarke, D.J. (2016) A theory of rational demand for index insurance. *American Economic Journal: Microeconomics*, 8, 283–306.

Coble, K.H. & Barnett, B.J. (2013) Why do we subsidize crop insurance? *American Journal of Agricultural Economics*, 95(2), 498–504.

Collier, B., Skees, J. & Barnett, B. (2009) Weather index insurance and climate change: opportunities and challenges in lower income countries. *The Geneva Papers on Risk Insurance-Issues Practice*, 34, 401–424.

Conradt, S., Finger, R. & Sporri, M. (2015) Flexible weather index-based insurance design. *Climate Risk Management*, 10, 106–117.

Dalhaus, T. & Finger, R. (2016) Can gridded precipitation data and phenological observations reduce basis risk of weather index–based insurance? *Weather, Climate, and Society*, 8, 409–419.

Delgado, C.L. (2003) *Fish to 2020: supply and demand in changing global markets*. Penang: WorldFish Center.

Deng, X., Barnett, B.J., Vedenov, D.V. & West, J.W. (2007) Hedging dairy production losses using weather-based index insurance. *Agricultural Economics*, 36, 271–280.

Fuchs, A. & Wolff, H. (2011) Concept and unintended consequences of weather index insurance: the case of Mexico. *American Journal of Agricultural Economics*, 93, 505–511.

Goodwin, B.K. & Smith, V.H. (2013) What harm is done by subsidizing crop insurance? *American Journal of Agricultural Economics*, 95(2), 489–497.

Hill, R.V., Hoddinott, J. & Kumar, N. (2013) Adoption of weather-index insurance: learning from willingness to pay among a panel of households in rural Ethiopia. *Agricultural Economics*, 44, 385–398.

Holly Wang, H. & Zhang, H. (2003) On the possibility of a private crop insurance market: a spatial statistics approach. *Journal of Risk & Insurance*, 70, 111–124.

Hotta, M. (1999) Fisheries insurance programmes in Asia: experiences, practices and principles. In: *FAO fisheries circular* No. 948. Rome: FAO.

Jensen, N. & Barrett, C. (2017) Agricultural index insurance for development. *Applied Economic Perspectives Policy*, 39, 199–219.

Jensen, N.D., Mude, A.G. & Barrett, C.B. (2018) How basis risk and spatiotemporal adverse selection influence demand for index insurance: evidence from northern Kenya. *Food Policy*, 74, 172–198.

Jensen, N.D., Stoeffler, Q., Fava, F., Vrieling, A., Atzberger, C., Meroni, M. et al. (2019) Does the design matter? Comparing satellite-based indices for insuring pastoralists against drought. *Ecological Economics*, 162, 59–73.

Joffre, O.M., Poortvliet, P.M. & Klerkx, L. (2018) Are shrimp farmers actual gamblers? An analysis of risk perception and risk management behaviors among shrimp farmers in the Mekong Delta. *Aquaculture*, 495, 528–537.

Le, T.C. & Cheong, F. (2010) Perceptions of risk and risk management in Vietnamese catfish farming: an empirical study. *Aquaculture Economics & Management*, 14, 282–314.

Leblois, A., Quirion, P., Alhassane, A. & Traore, S.B. (2014) Weather-index drought insurance: an ex ante evaluation for millet growers in Niger. *Environmental Resource Economics*, 57, 527–551.

Lu, S., Li, R., Zheng, W., Chen, L., Ren, Z., Mu, C. et al. (2019) Long-term low-salinity stress affects growth, survival and osmotic related gamma-aminobutyric acid regulation in the swimming crab Portunus trituberculatus. *Aquaculture Research*, 50, 2888–2895.

Mahul, O. (2001) Optimal insurance against climatic experience. *American Journal of Agricultural Economics*, 83, 593–604.

Manfredo, M.R. & Leuthold, R.M. (1999) Value-at-risk analysis: a review and the potential for agricultural applications. *Applied Economic Perspectives and Policy*, 21, 99–111.

Martin, S.W., Barnett, B.J. & Coble, K.H. (2001) Developing and pricing precipitation insurance. *Journal of Agricultural and Resource Economics*, 26, 261–274.

Miranda, M.J. & Farrin, K. (2012) Index insurance for developing countries. *Applied Economic Perspectives and Policy*, 34, 391–427.

Möhring, N., Dalhaus, T., Enjolras, G. & Finger, R. (2020) Crop insurance and pesticide use in European agriculture. *Agricultural Systems*, 184, 102902.

Norton, M.T., Turvey, C. & Osgood, D. (2013) Quantifying spatial basis risk for weather index insurance. *The Journal of Risk Finance*, 14, 20–34.

Ozaki, V.A., Goodwin, B.K. & Shirota, R. (2008) Parametric and nonparametric statistical modelling of crop yield: implications for pricing crop insurance contracts. *Applied Economics*, 40, 1151–1164.

Roberts, R.A. (2007) *Livestock and aquaculture insurance in developing countries*. Rome: FAO.

Romano, N. & Zeng, C. (2006) The effects of salinity on the survival, growth and haemolymph osmolality of early juvenile blue swimmer crabs, Portunus pelagicus. *Aquaculture*, 260, 151–162.

Salayo, N.D., Perez, M.L., Garces, L.R. & Pido, M.D. (2012) Mariculture development and livelihood diversification in The Philippines. *Marine Policy*, 36, 867–881.

Sherrick, B.J., Zanini, F.C., Schnitkey, G.D. & Irwin, S.H. (2004) Crop insurance valuation under alternative yield distributions. *American Journal of Agricultural Economics*, 86, 406–419.

Shi, H. & Jiang, Z. (2016) The efficiency of composite weather index insurance in hedging rice yield risk: evidence from China. *Agricultural Economics*, 47(3), 319–328.

Shirsath, P., Vyas, S., Aggarwal, P. & Rao, K.N. (2019) Designing weather index insurance of crops for the increased satisfaction of farmers, industry and the government. *Climate Risk Management*, 25, 100189.

Skees, J.R. (2008) Innovations in index insurance for the poor in lower income countries. *Agricultural Resource Economics Review*, 37, 1–15.

Skees, J.R. & Barnett, B.J. (2006) Enhancing microfinance using index-based risk-transfer products. *Agricultural Finance Review*, 66, 235–250.

Turvey, C.G. (2001) Weather derivatives for specific event risks in agriculture. *Applied Economic Perspectives Policy Research*, 23, 333–351.

Van Anrooy, R., Secretan, P.A.D., Lou, Y. & Roberts, R. (2006) *Review of the current state of world aquaculture insurance*. Rome: FAO.

Vedenov, D.V. & Barnett, B.J. (2004) Efficiency of weather derivatives as primary crop insurance instruments. *Journal of Agricultural and Resource Economics*, 29, 387–403.

Vroege, W., Bucheli, J., Dalhaus, T., Hirschi, M. & Finger, R. (2021) Insuring crops from space: the potential of satellite-retrieved soil moisture to reduce farmers' drought risk exposure. *European Review of Agricultural Economics*, 48, 266–314.

Wang, L., Pan, L., Ding, Y. & Ren, X. (2018) Effects of low salinity stress on immune response and evaluating indicators of the swimming crab Portunus trituberculatus. *Aquaculture Research*, 49, 659–667.

Ye, T., Hu, W., Barnett, B.J., Wang, J. & Gao, Y. (2020) Area yield index insurance or farm yield crop insurance? Chinese perspectives on Farmers' welfare and government subsidy effectiveness. *Journal of Agricultural Economics*, 71, 144–164.

Ye, T., Li, Y., Gao, Y., Wang, J. & Yi, M. (2017) Designing index-based livestock insurance for managing snow disaster risk in eastern Inner Mongolia, China. *International Journal of Disaster Risk Reduction*, 23, 160–168.

Ye, T. & Wang, M. (2013) Exploring risk attitude by a comparative experimental approach and its implication to disaster insurance practice in China. *Journal of Risk Research*, 16, 861–878.

Yuan, X., Pongthanapanich, T., Zhang, Z., Jing, X. & Ming, J. (2017) *Fishery and aquaculture insurance in China*. Rome, Italy: FAO.

Zant, W. (2008) Hot stuff: index insurance for Indian smallholder pepper growers. *World Development*, 36, 1585–1606.

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