https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

Review article: Design and Evaluation of Weather Index Insurance for Multi-Hazard Resilience and Food Insecurity

Marcos Roberto Benso[1], Gabriela Chiquito Gesualdo[1], Greicelene Jesus Silva[1], Luis Miguel Castilho Rápalo[1], Fabrício Alonso Richmond Navarro[1], Roberto Fray Silva[2], and Eduardo Mario Mendiondo[1]

[1]University of São Paulo, São Carlos School of Engineering, São Carlos, Brazil
[2]University of São Paulo, Polytechnic School, São Paulo, Brazil

Correspondence: Marcos R Benso (marcosbenso@gmail.com)

Abstract. The urgency of accelerating disaster risk resilience also promotes preferred systematic reviews of the methods for design and evaluation of risk transfer tools. This paper aims to provide a state-of-art weather index insurance design, thereby including methods for natural hazards' indices calculation, vulnerability assessment and risk pricing. We applied the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) using the Scopus database. First, 364 peer-reviewed articles from 2010 to present were screened for a bibliometric analysis and then, the 34 most cited articles from the past five years were systematically analyzed. Our results demonstrate that despite a great research effort on index insurance, the majority of them focused on food insecurity through agricultural and crop insurance. Also, climate change and basis risks were found highly relevant for weather index insurance, but weakly developed, suggesting challenges around food insecurity. Special focus was given to drought hazards, while other hazards such as temperature variation, excessive rainfall and wildfires were slightly covered. Emerging areas, namely agricultural, hydrological, and sustainable index insurance found promissory for insurance. Also, current state-of-the-art lacks methods for incorporating multi-hazard risk evaluation in vulnerability assessment and risk pricing. Most studies considered only single-hazard risk, and the multi-hazard risk studies assumed independence between hazards. Thus, we summarized the most common methods for calculating indices, estimating losses using indices, pricing risks, and evaluating insurance index policies. This review promotes a starting point in weather index insurance design towards a multi-hazard resilient society.

1 Introduction

The increased frequency and magnitude of extreme weather events have been evidenced in many regions of the globe, and it has been widely attributed to climate change IPCC, 2021. In the past years, extreme weather events have caused significant losses and damages in many climate-sensitive sectors. Insurance is an essential tool to provide economic sustainability to vulnerable sectors and improve recovery from catastrophic climate events. Kraehnert et al. (2021) argue that insurance itself is not an adaptation measure and depends on several characteristics and factors such as living standards, economic well-being, the availability of safety nets for poor people, characteristics of the sector, and the type of the risks the sectors are exposed to.

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

Insurance has been pointed as a tool for safeguarding population to climate change (UNEP, 2012). Re (2021) predicted non-life insurance premiums to rise 10% above the pre-pandemic state and acknowledges that climate change might have an even more significant impact on the industry. They propose that increasing underwriting policies against climate disasters is vital to tackle this problem. Nonetheless, the challenge might be more significant in developing countries with lower insurance coverage. In one hand, the the premiums per capita of the US and Canada were 7,270 USD, much higher than the world average of 809 USD and the Eurozone average of 2,723 USD. On the other hand, in Latin America and the Caribbean, and emerging Europe and Asia presented 203, 159 and 215 USD respectively. The numbers were much lower in Africa and the Emerging Middle East, representing 45 and 93 USD (Re, 2020).

Index-based insurance policy is a solution to improve insurance coverage, especially in low-income areas (Raucci et al., 2019). The term index insurance started being used for crop yield insurance policies based on area-yield indices as firstly described by Halcrow (1949) and then further revisited by Miranda (1991). The area-yield insurance model that was adopted in the US in the early 90's dividing agricultural areas in the crop domain into Group Risk Plans (GRP). Indemnities were triggered when forecasted crop yields would fall under a certain threshold (Skees, 2008).

Area-yield contracts depend on data availability and technical capacity to evaluate and monitor the group risk units, which can be costly and impractical in many poor and developing countries. To overcome this challenge, researchers proposed contracts based on weather indices. In the financial and actuarial literature, weather derivatives have been used to associate the financial frustration of a business with a weather index (Müller and Grandi, 2000). Contracts based on weather indices have helped policyholders to hedge against adverse conditions in the clothing business (Štulec et al., 2019), hydropower plants (Foster et al., 2015), and solar energy systems (Boyle et al., 2021). Crop yield contracts based on rainfall have been used due to their simplicity and data availability (Yoshida et al., 2019). The method uses rainfall from weather gauges nearby farms to predict losses, and the threshold is usually defined according to an index in the growing season.

This type of contract almost eliminates the need for in-site verification of losses, reducing administrative costs and improving the transparency of insurance products (Shirsath et al., 2019). Insurance companies also benefit from reducing moral hazards since crop losses are estimated from indices provided by third-party agencies (Ghosh et al., 2021). Moreover, due to reduced costs, contracts based on weather indices have been used for microinsurance contracts in poor rural areas to improve protection against adverse climate conditions and prevent smallholder farmers from falling into poverty traps (Skees, 2008). Despite the advantages, index insurance has a particular side effect called basis risk, which is a mismatch between actual losses and predicted losses (Ghosh et al., 2021).

As is expected from the relevance of agriculture in the insurance industry, most of the literature reviews focus on understanding index insurance and microinsurance for agriculture (Leblois et al., 2014; Sarris, 2013). Zara (2010) proposed a systematic review on the role of weather derivatives in the wine industry. Akter (2012) focused on reviewing particular problems of microinsurance in Bangladesh, looking for evidence for insurance demand, how to approach the market, and design challenges to improve the safety of the vulnerable population, especially for smallholder farmers.

Several studies have been reported on single hazard risk insurance design. Considering only one hazard does not include the expression of risk due to interactions among different hazards (Gill and Malamud, 2014; Hillier et al., 2020). The insurance risk

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

assessment and climate change impacts have been recently reviewed by (Lyubchich et al., 2019). The authors review several adverse events such as floods, hail and excessive wind, but the interaction effect between hazards was little discussed.

Sekhri et al. (2020) proposed a framework for multi-hazard risk management. However, their model was too specific for mountainous regions and a broader risk management strategy. Komendantova et al. (2014) introduced a framework for participatory risk governance, allowing for feedback from stakeholders. Nevertheless, the model does not generalize more specific risk management strategies. An extensive review of the possible index insurance applications for agriculture was conducted by Abdi et al. (2022). The authors summarize indices and methods for designing index insurance with possible applications for multi-hazard risks. However, the implementation of multi-hazards has not received nearly as thorough investigation as single-hazard problems.

Although significant advances have been made in index insurance design, very little further attention appears to have been given to a generalized approach. Moreover, less work has been performed on multi-hazard risk insurance than on single hazard risk. This paper provides insight into a generalized approach to designing index insurance for single and multi-hazard risks. The systematic review was designed to answer five questions: 1) how weather extremes are represented in index insurance? 2) What are the most common models to simulate losses due to weather extremes? 3) What are the most common sectors of index insurance policies? 4) how index insurance is priced? 5) What is the relevance of climate change on index insurance policies?

2 Methodology

To achieve the objective of this, a systematic review approach was used to retrieve articles related to index insurance design. The PRISMA protocol Liberati et al. (2009) and Scopus database were used to conduct the systematic literature review for data collection, because Scopus is the largest abstract and citation database of scientific papers and includes a wide range of subjects in the fields of technology, science, social sciences, medicine, humanities and arts (Scopus, 2022). A double-step analysis was used to analyze the data. First, a bibliometric analysis was performed on the selected papers of the last 10 years, and secondly, a critical analysis of the most cited papers of the last 5 years was performed to derive guidelines for index insurance design and evaluation.

2.1 Search definition, screening, and extraction of data

These five questions were addressed in a search using Scopus. We used English search terms that were developed following a three-step procedure. First, we defined the most important keywords. Then, we selected synonyms according to the authors' experiences. Lastly, we developed the search string using the Boolean operators according to Scopus standards for scoping title, abstract, and keywords.

– English keywords: multi-risk weather index insurance.

– English synonyms: multi-risk, risk, weather, climate, index, parametric, insurance, microinsurance, derivative.

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

– Search: TITLE-ABS-KEY ((risk (multi AND risk) OR portfolio) OR (index OR parametric) AND (insurance OR microinsurance OR derivative) AND (weather OR climate))

First, a screening process was applied to select scientific articles in English, Portuguese or Spanish. Review articles, books, book chapters, and conference proceedings were excluded from the analysis. Secondly, the studies from 2010 to 2022 were considered for bibliometric analysis. To refine the analysis, only the papers that presented a complete application of an index insurance or weather derivative design were selected. This selection was performed in two steps, first, the article's titles were used to include the articles that met the objectives of this study, and then the article's abstracts were used to refine the selection. Thirdly, the most cited papers from the last 5 years were analyzed in full text to perform a critical review of the most relevant recently published studies. Papers published in 2022 were still considered even though they were not likely to have been evaluated yet and therefore cited by other authors.

The systematic review process was performed following the guidelines of Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA). The process is divided into four steps (Figure 1). The first consists of the definition of the search strings based on research questions. From this step, 1192 was selected. The second step is the screening of the selected papers using the inclusion criteria, and included 365 studies. Many studies on the evaluation of index insurance demand and studies on traditional insurance models were excluded based on the evaluation of titles and abstracts. The studies screened in the second step were used in the bibliometric analysis. The third step required the full-text evaluation to exclude papers that did not provide information on index insurance design including (i) hazard, (ii) vulnerability, and (iii) financial analyses. Finally, 34 studies were used for the critical review of the literature.

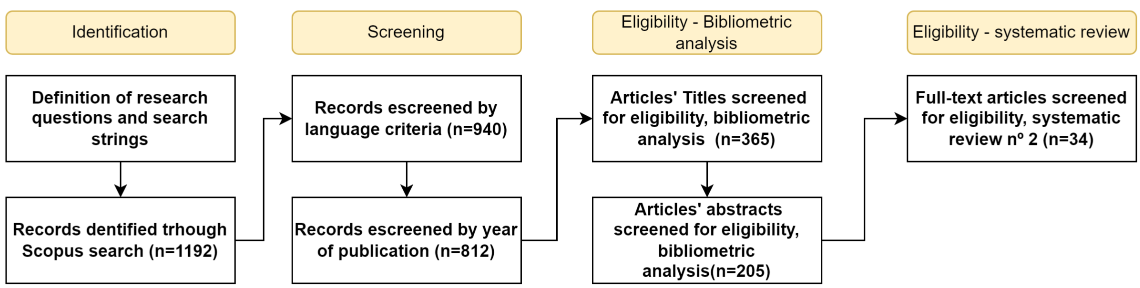

Figure 1. Methodological steps of PRISMA statement

2.2 Data analysis

To understand the current trend and development of weather index insurance, a bibliometric analysis was performed using the package bibliometrix (Aria and Cuccurullo, 2017) in R software. A global collaboration network was proposed. A co-word analysis was conducted using author's keywords that co-occurred in the studies. Lastly, a systematic analysis was developed in three steps that represent modules as described by Guzmán et al. (2020); Mohor and Mendiondo (2017); RIGHETTO et al. (2007). Hazard module: uses historic weather or modeling data to characterize hazards and acts as potential input to index

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

calculations. Vulnerability module: evaluate the impact of hazards using single or multi-sector. This step adds an economic dimension to environmental variables. Financial module: apply economic models for pricing premium rates and evaluating scenarios.

3 Results and Discussion

3.1 Bibliometric analysis

An increasing number of studies can be observed in recent years, with about 50% (n=198) of the articles being published since 2018, the number of average citations per year of the papers demonstrate and increasing impact of the weather index insurance in the literature (Figure 2a). However, the global distribution is concentrated in Europe, USA/Canada, and Asia being involved in 42, 26. and 20% of the papers published, respectively. The role of Latin America/Caribbean, Australia/New Zealand/Oceania and Africa are much lower representing 3, 7, and 2 %, respectively. International collaboration is a critical factor for high-impact scientific studies. In Russia, more than 90% of highly cited papers were written in an international setting (Pislyakov and Shukshina, 2014). Similarly, in China, 47% of highly cited papers were written in an international collaborative form. These papers highlight that partnerships with international scientists coming from centers of excellence benefit by increasing the dissemination of the study.

In the scientific collaboration map (Figure 2b), there are strong collaboration networks between the United States, European countries, China, and India. European countries such as Germany, Switzerland, and the Netherlands have played a dominant position in integration and have promoted collaboration with Kenia, Ethiopia, Nigeria, and South Africa. Canada has collaborated with China and Indonesia, besides the United States and European countries. From this analysis, we can conclude that the United States, China, and Germany play dominant positions in scientific collaboration and are the most influential countries.

Another significant observation is that most developing countries, especially on the South American and African continents, do not have relevant studies in the field. This is somewhat incoherent, as these countries suffer the most from extreme events losses due to their solid economic link with climate-dependent primary activities.

A strategic diagram is presented in Table 1 to analyze themes according to their centrality and density values. According to Cobo et al. (2011), the themes are clusters of keywords. The themes are plotted in a two-dimensional space that is classified in terms of the two aforementioned parameters ("density" and "centrality"). Density is a measure of the development of the theme, and centrality is the importance of the theme in the development of the whole field of research we analyzed.

Motor themes: these themes are well developed and relevant for the entire insurance theme. Since they present strong centrality and high density, the clusters "insurance", "agriculture" and "risk management" and the cluster "crop insurance" are conceptually related to almost all papers gathered in the bibliometric analysis. This result confirms that agricultural and crop insurance are the most explored themes in the index insurance field.

Niche themes: the theme "weather derivatives" is considered a niche theme because it is well developed, but has a marginal impact in the field. The themes have fundamental distinctions and similarities. Derivatives are traded Over the Counter (OTC)

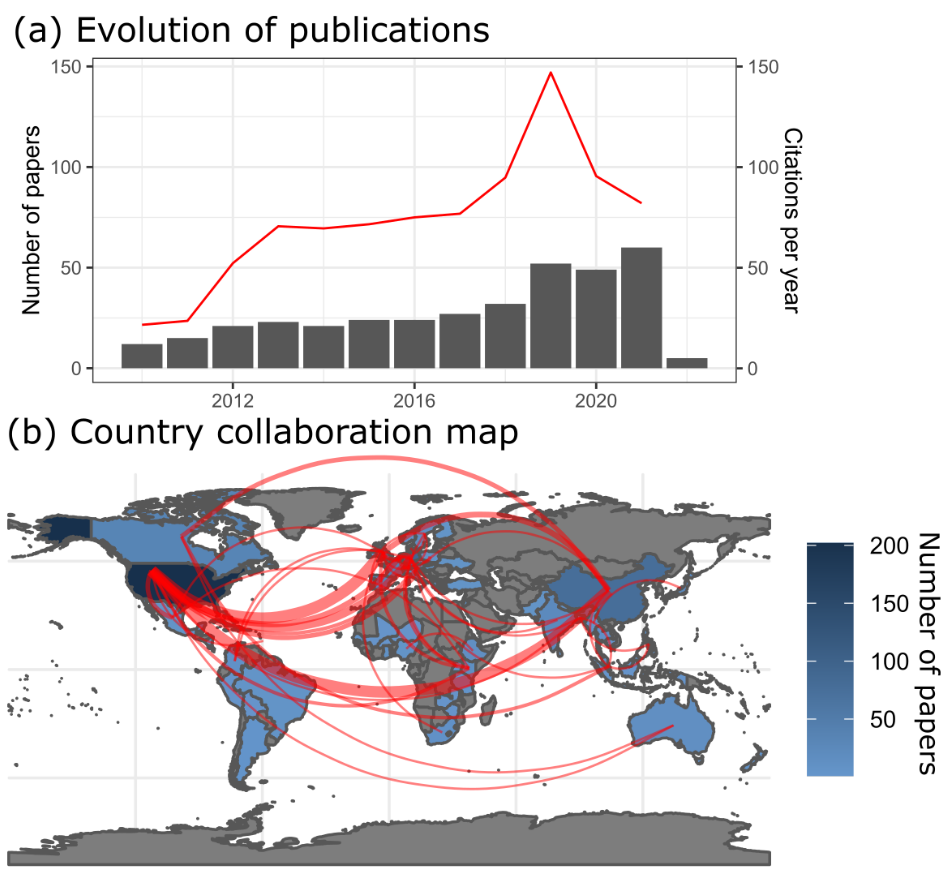

Figure 2. Weather index insurance studies. (a) Temporal distribution from 2010 to 2022. (b) Thematic map representing the global collaboration network, where the countries in blue represent the number of studies produced by scientists. The darker the color, the more affiliations. The world vector map data was provided by https://www.naturalearthdata.com/ under public domain.

or on Chicago Mercantile Exchange (CME). Index insurance is a product offered by insurance and reinsurance companies. They theoretically have a similar principle: a risk-averse individual pays a premium for a risk-bearing individual.

Emerging and declining themes: the themes in this quadrant represent the combination of low level of development and marginal to the entire field of research. This quadrant includes "weather index insurance", which is a critical issue in terms of impact since extreme weather events are significant disasters worldwide. Given the need to manage weather extremes and its importance to a broader geophysical community, we argue that weather index insurance is an emerging topic that will gain more attention in the following years.

Basic themes: these themes are relevant for the field; However, they are weakly developed. This quadrant includes the cluster "index-based insurance", the cluster "climate change", and the cluster "index insurance" and "basis risk". Climate change has been a significant concern for decision-makers, especially risk management. Changes in climate conditions might lead some regions toward higher risk profiles, increasing their vulnerability and the expected losses. Therefore, this theme represents an

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

Table 1. Thematic mapping of the documents based on the conceptual structure of the author's keywords divided into seven clusters with word frequency higher than 40 words according to centrality (the relevance of the theme in the development of the field) and density (the development of the field)

Theme	Cluster	Density	Centrality
Motor	Insurance	9	7
	Crop insurance	7	5
Niche	Weather derivative	2	8
Emerging and Declining	Weather index insurance	3	4
	Index-based insurance	5	3
Basic	Basis risk	8	1
	Climate change	6	2

opportunity for the development of index insurances. Basis risk is a primary topic that requires more development. Even though basis risk is a well-known bottleneck in the field, our analysis suggests room for improvements, and more attention to this topic must be paid in future studies.

3.2 Systematic literature review

For the systematic review, we defined agriculture (n=17), hydrologic (n=4), solar and wind power energy (n=3), derivatives (n=4), and multi-hazard risk (n=5) as primary categories of analysis. As expected from the bibliometric analysis, the literature focuses on agricultural insurance, while other emerging topics show potential irrigation, water supply, and energy production applications. Literature has overlooked multi-risk insurance, and our results presented only six studies on this topic. However, one failed to fit the inclusion criteria number 3 from Table 1 (The study presents an application of the development of index insurance, microinsurance, or weather derivative). The papers used considered for the systematic review are presented in the Supplementary Material Table S1.

3.2.1 Hazard identification

The index insurance literature shows a wider variety of analyzed hazards and employed indices. A summary of the indices found in the literature is portrayed in Figure 3 and a complete description is found in the Supplementary Material Table S2. Drought is the most frequent hazard (n = 19), followed by temperature variation (n = 5), excess rainfall (n = 4), cloud coverage (n = 2), fire (n = 1), storm (n = 1), and wind speed fluctuation (n = 1) and, water deficit (n = 1). More than half of the studies focused on drought. This can be explained by the fact that drought is the most harmful hazard in the agriculture sector. In addition, the agriculture sector was the motor theme of the reviewed studies. Our finding is consistent, since, between 1983 and 2009, drought has caused an equivalent of 217 billion USD from 1983 to 2009 (Kim et al., 2019).

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

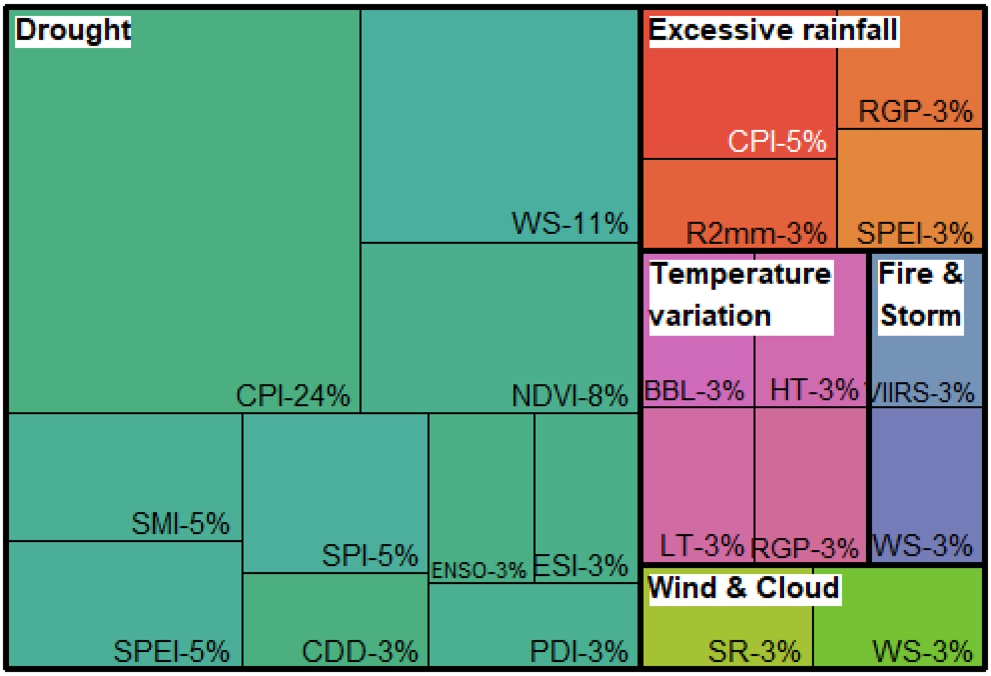

Figure 3. Tree map showing the proportion of indices for different hazards (dark green is drought, orange is excessive rainfall, magenta is temperature variation, blue is fire and storm, and light green is wind and cloud) employed in the reviewed studies. The number indicates the percentage of indices used in the studies including the studies that employed more than one index.

Drought is a complex natural disaster that affects several sectors such as agriculture, recreation and tourism, energy, and transportation. Usually, droughts are defined in four levels, meteorological drought, agricultural drought, hydrological drought, and socioeconomic drought (Wilhite and Glantz, 1985). Usually, meteorological drought represents precipitation deficit and is a proxy for other forms of droughts. Several papers approached rainfall-based drought indices, such as the Cumulative Precipitation Index (CPI) (Awondo, 2019; Kraehnert et al., 2021; Bokusheva, 2018; Bucheli et al., 2021; Kath et al., 2019; Turvey et al., 2019; Ward and Makhija, 2018; Shirsath et al., 2019). Consecutive dry days (CDD) is also a very straightforward strategy to indicate drought conditions because it accounts for the number of days without significant rainfall events (Shirsath et al., 2019).

Standardized Precipitation Index (SPI), which is more complex than CPI and CDD, can be used to incorporate weather statistics in the analysis. SPI uses monthly-accumulated precipitation and requires historical information to determine how much monthly rainfall deviates from average. The procedure requires assuming a distribution, that usually is gamma, and defining the mean and standard deviation to compute the index (Mckee et al., 1993). Rainfall-based indicators do not account directly for the interaction between soil and plant. Therefore, some authors suggest the use of potential evapotranspiration

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

(ET0) to calculate soil water balance such as in Standardized precipitation evapotranspiration index (SPEI) (Bucheli et al., 2021; Kapsambelis et al., 2019b) or using ET0 to calculate Evaporative Stress Index (ESI) (Bucheli et al., 2021).

Water soil balance offers a solution for estimating soil moisture. However, methods such as SPEI and ESI require data for radiation, temperature, and relative humidity, which can be very challenging for developing countries, where the density of weather stations is low. With the advances in modeling techniques, it is possible to improve soil moisture estimation (Seneviratne et al., 2010), especially with data from satellite missions such as Soil Moisture Active Passive (SMAP). (Entekhabi et al., 2010) stated that this data helped them calibrate balance models and increased model accuracy. However, the lack of ground stations is related to satellite estimations' biases (Chao et al., 2021). Soil moisture from ground stations and satellite imagery can help to detect droughts and be used as an index, such as Soil Moisture Index (SMI) (Bucheli et al., 2021; Vroege et al., 2021).

However, Bucheli et al. (2021) tested several indices. There was no clear indicator of a single optimized index that is generalized for all farms in the Lower-Saxony region in Germany. The authors concluded that indices are optimized for particular regions rather than regionally accepted as optimal. The Normalized Difference Vegetation Index (NDVI) is a satellite product based on red and near-infrared reflectance. It is a proxy for vegetation health and has been used as an index variable for insurance(Bucheli et al., 2021; Eze et al., 2020; F et al., 2020). The surface sea temperature of the Pacific Ocean has a close relationship with droughts in many parts of the globe, such as Central America, South Africa, Australia, and Southeast Asia (Vicente-Serrano et al., 2011). El Niño South Oscillation (ENSO) has demonstrated the potential to predict extreme drought conditions (Vicente-Serrano et al., 2011), therefore being used as a customized index for insurance design in Peru (Mortensen and Block, 2018). Lastly, customized indices can be used in situations where the relationships between droughts and losses and damages are very specific. The Ped Drought Index (PDI) was developed to address this problem by incorporating site-specific information into the CPI (Bokusheva, 2018).

Hydrological droughts can cause extensive damage to reservoirs for water supply, irrigation, or hydropower plants. Reservoirs are used to manage streamflow variations and can store water for more extended periods. Nonetheless, longer dry periods can cause shortages forcing operators to reduce capacity or even interrupt business. Water scarcity is a growing hazard, often related to hydrological droughts, and in most cases, requires hydrological modeling for predicting and forecasting water storage (Denaro et al., 2018; Gómez-Limón, 2020; Guerrero-Baena and Gómez-Limón, 2019; Mohor and Mendiondo, 2017).

Thermal hazard has been an emergent subject of interest for human health, crop production, forestry, and the environment. Increasing mean temperatures, mostly related to impacts of global warming, can be beneficial for crop production in the northern hemisphere (Rosenzweig et al., 2008). Nevertheless, the increasing frequency and magnitude of temperature extremes is a threat to crop production in the tropics, human health, and many other plant and animal species (Vasseur et al., 2014). Given the topic's relevance, it is anti-climax to conclude that we have found only three papers on temperature variation insurance. The indices focused on computing the number of days the temperature was higher or lower than a certain threshold High Temperature Index (HTI) and Low Temperature Index (LTI) (Guo et al., 2019).

Increasing temperature extremes attributed to climate change can reduce crop production, and most of this reduction will be experienced by developing countries (Rosenzweig et al., 2008). According to (Hatfield and Prueger, 2015), water deficit and

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

excess can potentially increase the impacts of extreme temperature conditions on crop production. The effects of the interaction of temperature and soil water show potential new areas of development in the insurance industry and should gain relevance in the next few years.

Thermal hazards play an essential role in weather derivatives. In terms of hazard selection, derivatives focused mainly on temperature variation employing indices such as Heating Degree Days (HDD) and Cooling Degree Days (HDD) (Alexandridis et al., 2021; Berhane et al., 2021; Gülpınar and Çanakoğlu, 2017). These studies overlooked overall risk assessment such as exposure and vulnerability while focusing on selecting distribution functions of temperatures and uncertainty of portfolios for the options market, with Chicago Mercantile Exchange (CME) contracts as a reference.

Even though soil water availability is critical for plant development, too much rainfall can limit crop yields and threaten farmers (Liu et al., 2021). Excessive rainfall affects tourists' decisions on where to travel, impacting regions that rely on tourism as an income source (Olya and Alipour, 2015). Moreover, excessive rainfall can impact floods, which is one of the most important hazards in terms of socio-economic impact (Hudson et al., 2019).

Excessive rainfall has been weakly developed in the papers analyzed in this study. Some applications to crop insurance use CPI (Kapsambelis et al., 2019b, a) and SPEI (D. Kapsambelis et al., 2019). The advantage of these indices mentioned above is that they can be used for water deficit and water excess studies. However, they account for more prolonged temporal impact hazards and do not account for short events with severe impacts. The response to this problem can be given using indices that account for the most significant precipitation sum within a specified period, such as R2mm (Kapsambelis et al., 2019a), which is the sum of two consecutive days when rainfall exceeds a specific rainfall.

Sacchelli et al. (2018) described a multi-hazard risk study for fires and storms' impact on forestry in Italy. Both forest fires (Flannigan et al., 2006) and storms (Hettiarachchi et al., 2018) are considered emerging hazards due to climate change. Sacchelli et al. (2018) described forest fires using Visible Infrared Imaging Radiometer Suite (VIIRS), an instrument onboard NASA's Suomi National Polar-orbiting Partnership (S-NPP) and Joint Polar Satellite System-1. The instruments collect several relevant information about land, ocean, atmosphere, and cryosphere with a 750 m resolution. The data provides important information about active global fires (Li et al., 2020) and is well suited for designing insurance policies. Sacchelli et al. (2018) explored the effects of strong winds caused by storms on the forest sector. The index is straightforward, is based on wind speed measured by weather stations, and is calculated every time wind speed exceeds a specific threshold value.

Sustainable energy production is vulnerable to variability and uncertainty of climate conditions (Bessa et al., 2014). We have discussed the problem of hydrological droughts in the drought section, and here we further explore the problem of wind (Rodríguez et al., 2021) and solar power (Boyle et al., 2021) production. Here we explore the wind index with a low threshold. The operation of wind power mills can be complicated if the average wind speed is lower than a certain threshold, therefore producing income losses for companies. The impact of cloud coverage was measured using weather gauge data on solar radiation, which follows a similar principle to the wind index. If average solar radiation falls below a specific value, power energy companies will suffer income losses.

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

3.2.2 Vulnerability analysis

The vulnerability analysis consists in understanding what asset is at risk and finding a relationship between the index and the impact. The vulnerability analysis implies that a certain Value is at Risk (VaR) or the extreme of the distribution, the Tail-Value at Risk (TVar). As defined by Farrag et al. (2022), this value is associated with the expected loss or damage for a given exceedance probability of a hydrometeorological variable. This value is used as a risk management metric and for insurance purposes, the time of return of the hydrometeorological variable is adjusted according to the degree of risk aversion of the individual exposed to a hazard, e.g., drought and excessive rainfall (Arshad et al., 2016). This hypothesis suggests that the VaR increases with the time or return and the severity of extreme events or from the combination of events, when multivariate distributions are evaluate – i.e. when considering the synergy or co-occurrence of more than one hazards (Brunner et al., 2021). The degree of risk aversion tend to increase, because the ecosystem services tend to be affected by the increasing of severity and frequency of hydrological extremes (Paul et al., 2020).

For farmers, climate-driven hazards such as droughts, temperature variation, excessive rainfall can decrease crop yields, cause damage to forests and cause livestock mortality (Bokusheva, 2018; Bucheli et al., 2021; Eze et al., 2020; Sacchelli et al., 2018; Vroege and Finger, 2020; Ward and Makhija, 2018). The lack of precipitation is very concerning for reservoir operation that leads to business interruption in the case of water supply and irrigation (Denaro et al., 2020; Gómez-Limón, 2020; Guerrero-Baena and Gómez-Limón, 2019; Mohor and Mendiondo, 2017).

We observed an emerging topic affecting sustainability with a focus on sustainable energy generation. We excluded hydropower from this category because reservoir operation frequently meets multiple demands, including water supply, irrigation, and maintenance of ecological flows. Wind power energy depends on average wind speed. Therefore, the lack of wind can cause income reduction (Rodríguez et al., 2021). A similar impact is faced by solar panels that depend on enough solar radiation to meet energy yield goals. Excessive cloud coverage can cause income reduction (Boyle et al., 2021; Matsumoto and Yamada, 2021).

Weather variables support risk analysis and are used to predict the financial impact. This is key for making index insurance robust and scalable to a level where operational costs can be reduced, and moral hazards can be neglected since the loss verification is performed from a monitored index. Basis risk, and it implies that there is a certain probability of a mismatch between modeled losses and actual losses. Basis risk assessment and reduction is an important topic and depends on the quality of input data and the characteristics of the sector. Further discussion on this topic can be found in Dalhaus et al. (2018); Götze and Gürtler (2022); Hochscherf (2017).

Deterministic models were applied for income reduction impacts, especially for crop insurance. Additionally, some models were related only with one explanatory variable (one index) was the most common solution found in the in-depth analysis (Aizaki et al., 2021; Bokusheva, 2018; Bucheli et al., 2021; Hohl et al., 2020; Kath et al., 2019; Mortensen and Block, 2018; F et al., 2020; Vroege and Finger, 2020; Ward and Makhija, 2018). There is evidence that machine learning techniques improve loss modeling from different sources and present different time and spatial scales (Eze et al., 2020). Another example is empirical functions that can be used when vulnerability studies for specific sites are available. Mohor and Mendiondo (2017)

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

presented empirical functions for predicting the impact of water shortage on water supply, irrigation, livestock, and ecological sectors.

Generalized Additive Linear Models (GALM) and stepwise regression added the possibility of evaluating more than one index, including the possibility of a multi-hazard approach (Awondo, 2019; Kath et al., 2018; Matsumoto and Yamada, 2021; Shirsath et al., 2019). A multi-hazard approach requires understanding the frequency of each hazard and its interaction. These interactions are complex, and several papers tried to tackle this problem (Decker and Brinkman, 2016; Gill and Malamud, 2014).

The multi-hazard risk index insurance papers presented combinations of drought and excessive rainfall for crop insurance (Kapsambelis et al., 2019b; Shirsath et al., 2019), fire and storms for forestry insurance (Sacchelli et al., 2018), temperature variation and excessive rainfall for crop insurance (Salgueiro, 2019) and high and low temperatures for crop insurance (Guo et al., 2019). The assumption of independence was considered prior knowledge by Salgueiro (2019) and Guo et al. (2019). However, the authors did not provide a mathematical proof of this choice; they prioritized hazards according to their frequency and magnitude using existent risk maps.

Droughts and excessive rainfall may be equally detrimental to agriculture (Hettiarachchi et al., 2018). El Niño-Southern Oscillation (ENSO) triggers extreme precipitation events (Lyon and Barnston, 2005), which makes the hypothesis of a compound event plausible in this case. Mortensen and Block (2018) proposed an insurance policy for droughts using ENSO as an index and obtained good crop losses prediction accuracy. Nonetheless, in a multi-hazard risk schema, this variable should be considered to improve the model's ability to evaluate the probability of extreme precipitation events related to ENSO or other larger-scale meteorological phenomena that impact a region.

Copulas had been used for incorporating hazard interaction in the loss modeling Kapsambelis et al. (2019b); Salgueiro (2019). The copula theory (Nelsen, 2006) has been widely used for multi-hazard analysis since it derives joint probability distributions from marginal distributions. Briefly, the marginal distributions are not required to follow the same probability distribution model giving flexibility and robustness to analyze the interaction of more than two marginal distributions much easier than complicated multivariate probabilistic models. The vulnerability models are summarised in the Supplementary Material Table S3.

3.2.3 Financial methods and risk pricing

The vulnerability module provides tools for modeling the relationship between single or multi-hazards and their impact on the sector. This impact can be translated as actual damage, income reduction, or business interruption. These losses are modeled using crop yields as a proxy variable for crop insurance. This is done by assuming a minimum crop yield value that represents the expectation of farmers or even the value they need to obtain to prevent them from going bankrupt. In terms of modeling, this is straightforward because the relationship between weather variables and crop yields has been extensively documented (Allen et al., 1998). For hydrological insurance, when streamflow are low, water utility services might suffer interruption or be unable to operate given the extreme condition. Business interruption can increase the water supply services price and make

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

farmers susceptible to losses. For sustainable insurance, which is the case of solar power, wind power, and hydropower, there is an income reduction caused by the low performance of the system.

In the literature review, we found that the papers considered that the historical losses could be translated as payouts, including two critical variables, strike values K and degree of coverage . The strike value is an index value that triggers payouts and is proportional to risk aversion. Risk aversion also causes policyholders to choose different degrees of coverage ranging from 0 to 1, being 0 no protection and 1 full protection. These parameters reflect the behavior and aversion that policyholders present towards a particular risk and will define the amount of money insurance companies will pay to policyholders if an extreme event occurs.

Put and call options were consistently found in the papers we analyzed and reflect common structures found in weather derivatives (Stephan and Brix, 2005). The call option is used for indices triggered when their value exceeds a threshold, such as excessive rainfall and high temperatures. On the other hand, the put option is used for indices that fall below a threshold, such as droughts, low streamflow, cloud coverage, and wind speed. Both contract models portray a linear relationship with the index. However, different arrangements can be made, such as swaps, put, call, strangle and straddles. These contract formats and more are described further by Stephan and Brix (2005).

Other approaches for defining contract payouts are based on a probabilistic framework. Bokusheva (2018) applied the Marginal Expected Shortfall (MES) method, which is a conditional probability modeling where payouts are given when the target variable exceeds the strike value. Eze et al. (2020) used cluster analysis comparing NDVI with crop yields to define different strike values, they created clusters associating NDVI and weather values grouped with higher yields observations. The indices values showing dry conditions or less favorable crop development were associated with lower observed crop yields.

The economic model of competitive markets with full information predicts the price of pure risk premiums using expected losses. They are calculated historical data from the individuals or companies and use the mean historical losses to estimate expected future losses for similar sectors (Sant, 1980) . The expected losses are called pure risk premiums and are the major concern in index insurance papers. Index insurance has a slightly different rationale, the losses are modeled using indices, and then the pure risk is calculated.

The loss expectation can be determined using historical burn rate method (HBR), which is the mean historical losses (Guerrero-Baena and Gómez-Limón, 2019; Hohl et al., 2020; Mortensen and Block, 2018; Shirsath et al., 2019).This method is widely applied in the insurance industry, however, requires sufficient data in order to be accurate. For smaller datasets considering uncertainty, expected values can be evaluated by fitting loss data to a probability density function (Aizaki et al., 2021; Bokusheva, 2018; Bucheli et al., 2021; Eze et al., 2020; Kath et al., 2019; Salgueiro, 2019; Sacchelli et al., 2018; Vroege et al., 2021; Ward et al., 2020).

This procedure helps to improve pure risk premium rates by accounting for the probability of extreme events that have not been recorded. The probability distribution of loss data presents distortions in the tails, leading to underestimating pure risk premiums. Moreover, insurance companies present nontraded assets that add costs to final premium rates. This can be overcome by a transformation proposed by Wang (2002), and the methodology was applied for pricing premiums by Boyle et al. (2021); Denaro et al. (2018).

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

It is well known that climate variables present a certain degree of uncertainty that needs to be considered when estimating losses caused by climate-related losses (Smith and Matthews, 2015). A stochastic approach based on Monte Carlo simulations is used in the literature to address the problem. R Monte Carlos simulation is the basis of index modeling method applied by Alexandridis et al. (2021); Berhane et al. (2021); Gómez-Limón (2020); Gülpınar and Çanakoḡlu (2017); Guo et al. (2019); Kapsambelis et al. (2019b); Salgueiro (2019); Mohor and Mendiondo (2017); Rodríguez et al. (2021). The generation of synthetic weather time series enhances understanding the climate uncertainty in terms of confidence intervals. A summary of the risk pricing methods is described in the Supplementary Material table S4.

Econometric models provide values that guide decision-makers in understanding the price of the risk. However, it is fundamental to evaluate the risk reduction performance of index insurance. The simulation of cash flows allows understanding of the hedging effectiveness of the insurance policy. Nonetheless, this efficiency depends on the point of reference adopted by the modeler. The effectiveness problem arises when policyholders and insurance companies have different objectives. On the one hand, policyholders want to increase the protection of their assets at risk to prevent going out of business, on the other hand, insurance companies want to maximize profit to comply with the interests of their investors and shareholders. Since information asymmetry and moral hazards are allegedly minimized in the case of index insurance (Barnett et al., 2008; Mußhoff et al., 2018), the costs associated with moral hazards can be neglected from premium rates pricing.

The cash flow equation is a standard tool for evaluating the capital of companies and people. The simulation of cash flows using expected revenue and payouts as assets and premiums as liability for policyholders is used for evaluating the effectiveness of the index insurance policy (Bokusheva, 2018; Boyle et al., 2021; Kath et al., 2019; Salgueiro, 2019; Ward and Makhija, 2018). For insurance companies, the cash flow changes the direction, i.e., premiums are considered assets and payouts as a liability. This was used for calculating the loss ratio (Mohor and Mendiondo, 2017).

Other authors have applied the utility theory to evaluate insurance policies. The utility theory accounts for the behavior and individual preferences in the economic analysis and is based on some assumptions that apply to a group of individuals (Kahneman and Tversky, 1979). Some authors (Bucheli et al., 2021; Eze et al., 2020; Furuya et al., 2021; Ricome et al., 2017; Vroege et al., 2021; Ward and Makhija, 2018) used the concept of risk-averse utility functions for policyholders, where the asset's utility at risk is concave or diminishing. The utility function depends on the degree of risk aversion of the individuals, which influences their willingness to pay for an insurance policy. In theory, premium rates are maximized to meet the level of risk aversion of individuals, which influences insurance coverage and strike values. Finally, we present a conceptual framework derived from the literature review representing the weather index insurance design process (Figure 4).

From the literature review, we propose an overview of agricultural, hydrological and sustainable insurance, their application, and the most relevant characteristics Table (2). We observed that the studies evaluated insurance at different spatiotemporal aggregation. For crop insurance, the studies carried out analysis at farm level from governmental agencies, insurance companies or surveys. For many countries, agricultural data is aggregated at regional scale, i.e., municipality, department, state, country. The size of the properties varied from 5 to 400 hectares and the total coverage was up to 1.6 million hectares. Forestry insurance covers larger areas and uses remote sense data to assess risk, therefore, the spatial discretization is performed at pixel level. Hydrological insurance was calculated at catchment level and the coverage took into account all the hydrological processes

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

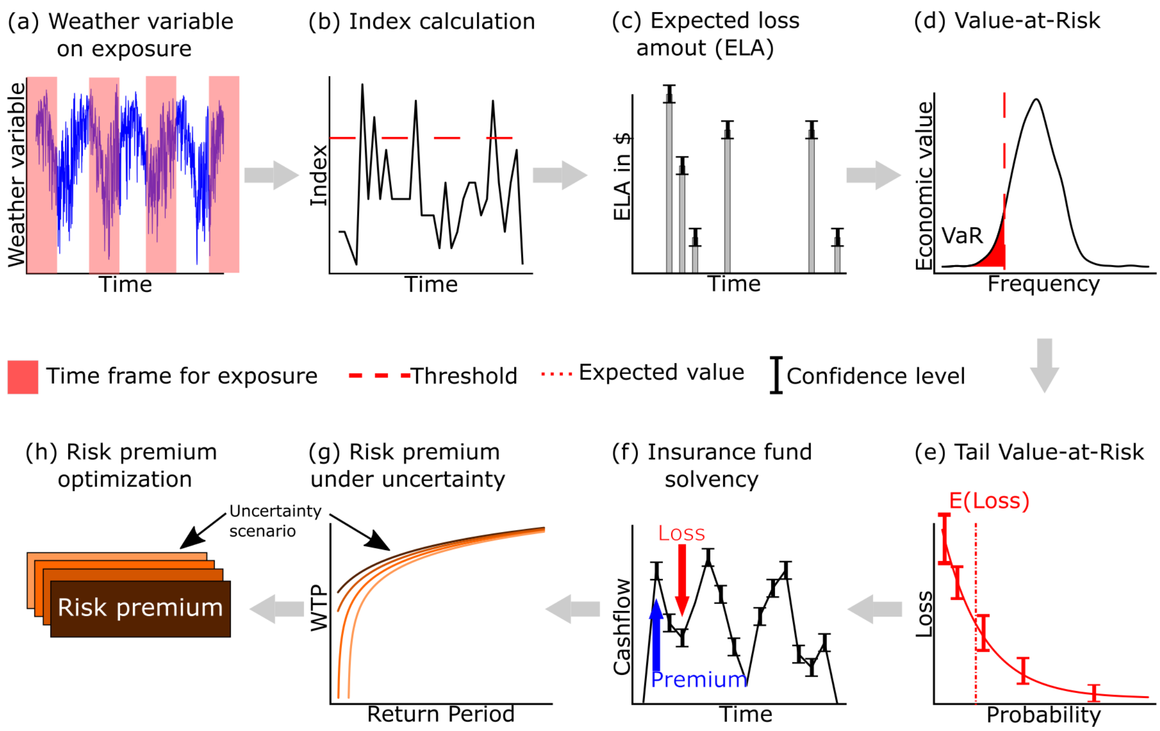

Figure 4. Conceptual framework for weather index insurance design including steps for hazard evaluation (a) and (b), vulnerability analysis (c) and (d), and financial risk pricing (e) and (e) and (f)

that occur upstream the reservoir. Finally, for wind and solar power insurance, only the point location of the windmills and solar panels was evaluated. The time frame in which the insurance was purchased varied from seasonal scale to annual scale. Crop insurance is normally contracted before the sowing period and reaches maturity at the end of the crop cycle. Sectors that are continuously exposed to natural hazards are operated on an annual basis. A summary of the policy evaluation methods is described in the Supplementary Material Table S5.

The risk-perception as a product of the experience of extreme events increases the VaR of users, therefore their risk-aversion expressed in terms of WTP. Moreover, this user would present a higher Willingness to Accept (WTA) (Baumgärtner and Strunz, 2014) and this is an important factor for demand for insurance contracts based on extreme events with lower frequency, but higher degree of severity (Spangenberg and Settele, 2010). The WTP for insurance policy premiums were represented using different units. The studies focused on the amount of premium per unit of area, unit of cost and proxy for local economy making results comparable. For crop insurance varied from \$6.18 to \$55.26 USD per hectare, this value was affected mostly by the cost of producing the crop and degree of risk aversion of farmers. A value of \$187.29 of USD per ton of crop and 3 to 7% of production costs were also found. Hydrological insurance for water supply represents values of \$10.48 and for irrigation a range of \$212.83-\$333.07 USD per hectare were presented. The prices for irrigation were inconsistent with the

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

Table 2. Main topics for index based insurance and specific application

Author	Application	Hazard	Area ha	Type of Area	Time Frame	WTP (Premium)
			Agriculture			
Bucheli et al. (2021)	Crop	Drought	1.0x106	Farm	Seasonal	$34.42
Kapsambelis et al. (2019b)	Crop	Multi-hazard	-	Department	Seasonal	$187.29
Guo et al. (2019)	Crop	Multi-hazard	-	Department	Seasonal	$35.29
Shirsath et al. (2019)	Crop	Drought	1.6x106	Farm	Seasonal	$9.88
Vroege et al. (2021)	Crop	Drought	400	Farm	Seasonal	$23.62-$48.10
Ricome et al. (2017)	Crop	Drought	15.2	Farm	Seasonal	$4.59-$8.44
Sacchelli et al. (2018)	Forestry	Fire, storm	1	Pixel	Annual	$22.90-$44.81
Kath et al. (2019)	Crop	Drought	-	Department	Seasonal	$6.18-$55.26
Furuya et al. (2021)	Crop	Flood	5.57	Farm	Annual	$7.45
Hohl et al. (2020)	Crop	Drought	24	Farm	Seasonal	$7.70
Kath et al. (2018)	Crop	Drought	-	Farm	Seasonal	$8.64-$41.03
Mortensen and Block (2018)	Crop	Drought	-	Department	Seasonal	3%-7%
Kath et al. (2018)	Crop	Drought	-	Department	Seasonal	$6.18*
			Hydrological			
Mohor and Mendiondo (2017)	Water supply	Water deficit	27,700 – 97,200	Catchment	Annual	0.10-0.44
Gómez-Limón (2020)	Irrigation	Water deficit	35.5	Farm	Seasonal	$212.83-$333.07*
Denaro et al. (2018)	Water supply	Water deficit	455.2	Catchment	Annual	$10.48
			Sustainable			
Boyle et al. (2021)	Solar power	Solar energy fluctuation	-	Location	Annual	0.35%-0.50
Rodríguez et al. (2021)	Wind power	Wind speed fluctuation	-	Location	Annual	$0.033144

other crop insurances and these values might be related to the operation costs of irrigation. Sustainable insurances presented premium rates ranging from 0.35 to 0.50 of production costs or a percentage of $0.033144 per kWh. As a thought exercise, if we extrapolate this value for the 20 GW of wind power generated in Brazil in 2021, insurance companies would receive an amount of 5.81 billion dollars.

4 Conclusions

This study reviewed the development and design of index insurance. By performing a bibliometric analysis of relevant studies from 2010 to 2022, a low academic interaction between Latin American countries and the world was observed. Moreover, a co-word analysis of the keywords demonstrated that agriculture and crop insurance are well-developed themes with a high impact on index insurance. The analysis showed that climate change and basis risk are essential in developing index insurance.

However, they are weakly developed. Developing countries such as Brazil, Argentina, and Mexico play a critical role in global food production (Baldos et al., 2020).

Furthermore, these tropical countries are more likely to experience a reduction in food production due to climate change (Rosenzweig and Parry, 1994). These results outline the importance of developing index insurance in South America, including climate change and reducing basis risks under water-ecology-food constraints. The systematic literature review focused on the most cited papers in the last five years to understand the most recent methods used and potential gaps in the field. The analysis focused on three modules: hazard, vulnerability, and financial. Drought is the most studied hazard; this is explained by the impacts of droughts on agriculture, the most researched topic. The index insurance literature is grounded in agriculture (Miranda, 1991; Skees, 2008) and, as the concept has gained attention, a broader range of applications might be proven feasible. The analysis of hazards suggests potential applications such as hydrological and sustainable insurance. Hydrological insurance focuses on the maintenance of water for reservoirs, and sustainable insurance focuses on clean energy such as solar panels and wind turbines.

In terms of hazard selection, most studies present single hazard risk, and the ones that present multi-hazard risk assume no interaction between hazards. The interaction between hazards is a significant concern when analyzing multi-hazard risks (Tilloy et al., 2019). Working with multi-hazard risk in agriculture is highly recommended since the sector is the motor theme in index insurance literature, and farmers are exposed to multiple sources of climate risk. This study proposed a conceptual framework for index insurance design. We gathered a set of methods for index selection, loss modeling, insurance premiums ratings, and index insurance policy evaluation from the systematic literature review. We suggested a rationale for determining the scope of the policy, allowing the design of single and multi-hazard risks and the application in different sectors.

Author contributions. Conception and design of the work: MRB. Data collection: MRB. Systematic Literature review: MRB, GCG, GJS, LCR, FARN, RFS. Discussion and analysis: MRB, GCG, GJS, LCR, FARN, RFS, EMM. Drafting the article: MRB. Critical review of the article: MRB, GCG, GJS, LCR, FARN, RFS, EMM. Advisor: EMM

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements. This study was supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior do Brasil (CAPES) - finance Code 001, and regular funding to post-graduate program in Hydraulics and Sanitation of University of Sao Paulo, São Carlos School of Engineering by the Brazilian National Council for Scientific and Technological Development (CNPq). Also, by the National Institute of Science and Technology for Climate Change Phase 2 (INCT-II) under the CNPq Grant 465501/2014-1, the São Paulo Research Support Foundation (FAPESP) Grant 2014/50848-9 and the CAPES Grant 16/2014.

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

References

Abdi, M. J., Raffar, N., Zulkafli, Z., Nurulhuda, K., Rehan, B. M., Muharam, F. M., Khosim, N. A., and Tangang, F.: Index-based insurance and hydroclimatic risk management in agriculture: A systematic review of index selection and yield-index modelling methods, International Journal of Disaster Risk Reduction, 67, 102 653, 2022.

Aizaki, H., Furuya, J., Sakurai, T., and Mar, S. S.: Measuring farmers' preferences for weather index insurance in the Ayeyarwady Delta, Myanmar: a discrete choice experiment approach, Paddy and Water Environment, 19, 307–317, https://doi.org/10.1007/s10333-020-00838-z, 2021.

Akter, S.: The Role of Microinsurance as a Safety Net Against Environmental Risks in Bangladesh, The Journal of Environment & Development, 21, 263–280, https://doi.org/10.1177/1070496512442505, 2012.

Alexandridis, A. K., Gzyl, H., ter Horst, E., and Molina, G.: Extracting pricing densities for weather derivatives using the maximum entropy method, Journal of the Operational Research Society, 72, 2412–2428, https://doi.org/10.1080/01605682.2020.1796532, 2021.

Allen, R. G., Pereira, L. S., Raes, D., Smith, M., et al.: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, Fao, Rome, 300, D05 109, 1998.

Aria, M. and Cuccurullo, C.: bibliometrix: An R-tool for comprehensive science mapping analysis, Journal of informetrics, 11, 959–975, 2017.

Arshad, M., Amjath-Babu, T., Kächele, H., and Müller, K.: What drives the willingness to pay for crop insurance against extreme weather events (flood and drought) in Pakistan? A hypothetical market approach, Climate and Development, 8, 234–244, https://doi.org/10.1080/17565529.2015.1034232, 2016.

Awondo, S. N.: Efficiency of region-wide catastrophic weather risk pools: Implications for African Risk Capacity insurance program, Journal of Development Economics, 136, 111–118, https://doi.org/10.1016/j.jdeveco.2018.10.004, 2019.

Baldos, U., Haqiqi, I., Hertel, T., Horridge, M., and Liu, J.: SIMPLE-G: A multiscale framework for integration of economic and biophysical determinants of sustainability, Environmental Modelling & Software, 133, 104 805, https://doi.org/10.1016/j.envsoft.2020.104805, 2020.

Barnett, B. J., Barrett, C. B., and Skees, J. R.: Poverty Traps and Index-Based Risk Transfer Products, World Development, 36, 1766–1785, https://doi.org/10.1016/j.worlddev.2007.10.016, 2008.

Baumgärtner, S. and Strunz, S.: The economic insurance value of ecosystem resilience, Ecological Economics, 101, 21–32, https://doi.org/10.1016/j.ecolecon.2014.02.012, 2014.

Berhane, T., Shibabaw, A., Awgichew, G., and Walelgn, A.: Pricing of weather derivatives based on temperature by obtaining market risk factor from historical data, Modeling Earth Systems and Environment, 7, 871–884, https://doi.org/10.1007/s40808-020-00925-4, 2021.

Bessa, R., Moreira, C., Silva, B., and Matos, M.: Handling renewable energy variability and uncertainty in power systems operation, Wiley Interdisciplinary Reviews: Energy and Environment, 3, 156–178, https://doi.org/10.1002/wene.76, 2014.

Bokusheva, R.: Using copulas for rating weather index insurance contracts, Journal of Applied Statistics, 45, 2328–2356, https://doi.org/10.1080/02664763.2017.1420146, 2018.

Boyle, C. F., Haas, J., and Kern, J. D.: Development of an irradiance-based weather derivative to hedge cloud risk for solar energy systems, Renewable Energy, 164, 1230–1243, https://doi.org/10.1016/j.renene.2020.10.091, 2021.

Brunner, M. I., Slater, L., Tallaksen, L. M., and Clark, M.: Challenges in modeling and predicting floods and droughts: A review, Wiley Interdisciplinary Reviews: Water, 8, e1520, https://doi.org/10.1002/WAT2.1520, 2021.

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

Bucheli, J., Dalhaus, T., and Finger, R.: The optimal drought index for designing weather index insurance, European Review of Agricultural Economics, 48, 573–597, https://doi.org/10.1093/erae/jbaa014, 2021.

Chao, L., Zhang, K., Wang, J., Feng, J., and Zhang, M.: A Comprehensive Evaluation of Five Evapotranspiration Datasets Based on Ground and GRACE Satellite Observations: Implications for Improvement of Evapotranspiration Retrieval Algorithm, Remote Sensing, 13, 2414, https://doi.org/10.3390/rs13122414, 2021.

Cobo, M., López-Herrera, A., Herrera-Viedma, E., and Herrera, F.: An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field, Journal of Informetrics, 5, 146–166, https://doi.org/10.1016/j.joi.2010.10.002, 2011.

Dalhaus, T., Musshoff, O., and Finger, R.: Phenology Information Contributes to Reduce Temporal Basis Risk in Agricultural Weather Index Insurance, Scientific Reports, 8, https://doi.org/10.1038/s41598-017-18656-5, 2018.

Decker, K. and Brinkman, H.: No Title, List of external hazards to be considered in ASAMPSA _ E (IRSN-PSN-RES-SAG–, pp. 11–2017, 2016.

Denaro, S., Castelletti, A., Giuliani, M., and Characklis, G.: Fostering cooperation in power asymmetrical water systems by the use of direct release rules and index-based insurance schemes, Advances in Water Resources, 115, 301–314, https://doi.org/10.1016/j.advwatres.2017.09.021, 2018.

Denaro, S., Castelletti, A., Giuliani, M., and Characklis, G.: Insurance Portfolio Diversification Through Bundling for Competing Agents Exposed to Uncorrelated Drought and Flood Risks, Water Resources Research, 56, https://doi.org/10.1029/2019WR026443, 2020.

Entekhabi, D., Njoku, E. G., O'Neill, P. E., Kellogg, K. H., Crow, W. T., Edelstein, W. N., Entin, J. K., Goodman, S. D., Jackson, T. J., Johnson, J., Kimball, J., Piepmeier, J. R., Koster, R. D., Martin, N., McDonald, K. C., Moghaddam, M., Moran, S., Reichle, R., Shi, J. C., Spencer, M. W., Thurman, S. W., Tsang, L., and Van Zyl, J.: The soil moisture active passive (SMAP) mission, Proceedings of the IEEE, 98, 704–716, https://doi.org/10.1109/JPROC.2010.2043918, 2010.

Eze, E., Girma, A., Zenebe, A., and Zenebe, G.: Feasible crop insurance indexes for drought risk management in Northern Ethiopia, International Journal of Disaster Risk Reduction, 47, https://doi.org/10.1016/j.ijdrr.2020.101544, 2020.

F, S., S, D. P., and E, B.-M.: Multi-scale remote sensing to support insurance policies in agriculture: from mid-term to instantaneous deductions, GIScience & Remote Sensing, 57, 770–784, https://doi.org/10.1080/15481603.2020.1798600, 2020.

Farrag, M., Brill, F., Dung, N. V., Sairam, N., Schröter, K., Kreibich, H., Merz, B., de Bruijn, K. M., and Vorogushyn, S.: On the role of floodplain storage and hydrodynamic interactions in flood risk estimation, Hydrological Sciences Journal, 67, 508–534, https://doi.org/10.1080/02626667.2022.2030058, 2022.

Flannigan, M. D., Amiro, B. D., Logan, K. A., Stocks, B. J., and Wotton, B. M.: Forest Fires and Climate Change in the 21ST Century, Mitigation and Adaptation Strategies for Global Change 2005 11:4, 11, 847–859, https://doi.org/10.1007/S11027-005-9020-7, 2006.

Foster, B., Kern, J., and Characklis, G.: Mitigating hydrologic financial risk in hydropower generation using index-based financial instruments, Water Resources and Economics, 10, 45–67, https://doi.org/10.1016/j.wre.2015.04.001, 2015.

Furuya, J., Mar, S. S., Hirano, A., and Sakurai, T.: Optimum insurance contract of flood damage index insurance for rice farmers in Myanmar, Paddy and Water Environment, 19, 319–330, https://doi.org/10.1007/s10333-021-00859-2, 2021.

Ghosh, R. K., Gupta, S., Singh, V., and Ward, P. S.: Demand for Crop Insurance in Developing Countries: New Evidence from India, Journal of Agricultural Economics, 72, 293–320, https://doi.org/10.1111/1477-9552.12403, 2021.

Gill, J. C. and Malamud, B. D.: Reviewing and visualizing the interactions of natural hazards, Reviews of Geophysics, 52, 680–722, https://doi.org/10.1002/2013RG000445, 2014.

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

Gómez-Limón, J. A.: Hydrological drought insurance for irrigated agriculture in southern Spain, Agricultural Water Management, 240, 106 271, https://doi.org/10.1016/j.agwat.2020.106271, 2020.

Götze, T. and Gürtler, M.: Risk transfer beyond reinsurance: the added value of CAT bonds, The Geneva Papers on Risk and Insurance-Issues and Practice, 47, 125–171, 2022.

Guerrero-Baena, M. and Gómez-Limón, J.: Insuring Water Supply in Irrigated Agriculture: A Proposal for Hydrological Drought Index-Based Insurance in Spain, Water, 11, 686, https://doi.org/10.3390/w11040686, 2019.

Gülpınar, N. and Çanakoğlu, E.: Robust portfolio selection problem under temperature uncertainty, European Journal of Operational Research, 256, 500–523, 2017.

Gülpınar, N. and Çanakoğlu, E.: Robust portfolio selection problem under temperature uncertainty, European Journal of Operational Research, 256, 500–523, https://doi.org/10.1016/j.ejor.2016.05.046, 2017.

Guo, J., Jin, J., Tang, Y., and Wu, X.: Design of temperature insurance index and risk zonation for single-season rice in response to high-temperature and low-temperature damage: A case study of Jiangsu province, China, International Journal of Environmental Research and Public Health, 16, https://doi.org/10.3390/ijerph16071187, 2019.

Guzmán, D. A., Mohor, G. S., and Mendiondo, E. M.: Multi-Year Index-Based Insurance for Adapting Water Utility Companies to Hydrological Drought: Case Study of a Water Supply System of the Sao Paulo Metropolitan Region, Brazil, Water, 12, 2954, https://doi.org/10.3390/w12112954, 2020.

Halcrow, H. G.: Actuarial Structures for Crop Insurance, Journal of Farm Economics, 31, 418, https://doi.org/10.2307/1232330, 1949.

Hatfield, J. L. and Prueger, J. H.: Temperature extremes: Effect on plant growth and development, Weather and Climate Extremes, 10, 4–10, https://doi.org/10.1016/j.wace.2015.08.001, 2015.

Hettiarachchi, S., Wasko, C., and Sharma, A.: Increase in flood risk resulting from climate change in a developed urban watershed – the role of storm temporal patterns, Hydrology and Earth System Sciences, 22, 2041–2056, https://doi.org/10.5194/hess-22-2041-2018, 2018.

Hillier, J. K., Matthews, T., Wilby, R. L., and Murphy, C.: Multi-hazard dependencies can increase or decrease risk, Nature Climate Change, 10, 595–598, https://doi.org/10.1038/s41558-020-0832-y, 2020.

Hochscherf, J.: Income heterogeneity and index insurance demand, Zeitschrift für die gesamte Versicherungswissenschaft, 106, 343–368, https://doi.org/10.1007/s12297-017-0386-x, 2017.

Hohl, R., Jiang, Z., Vu, M. T., Vijayaraghavan, S., and Liong, S.-Y.: Using a regional climate model to develop index-based drought insurance for sovereign disaster risk transfer, Agricultural Finance Review, 2020.

Hudson, P., Botzen, W. W., and Aerts, J. C.: Flood insurance arrangements in the European Union for future flood risk under climate and socioeconomic change, Global Environmental Change, 58, 101 966, https://doi.org/10.1016/j.gloenvcha.2019.101966, 2019.

Kahneman, D. and Tversky, A.: Prospect Theory: An Analysis of Decision under Risk, Econometrica, 47, 263, https://doi.org/10.2307/1914185, 1979.

Kapsambelis, D., Moncoulon, D., and Cordier, J.: An Innovative Damage Model for Crop Insurance, Combining Two Hazards into a Single Climatic Index, Climate, 7, 125, https://doi.org/10.3390/cli7110125, 2019a.

Kapsambelis, D., Moncoulon, D., and Cordier, J.: An innovative damage model for crop insurance, combining two hazards into a single climatic index, Climate, 7, 125, 2019b.

Kath, J., Mushtaq, S., Henry, R., Adeyinka, A., and Stone, R.: Index insurance benefits agricultural producers exposed to excessive rainfall risk, Weather and Climate Extremes, 22, 1–9, https://doi.org/10.1016/J.WACE.2018.10.003, 2018.

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

Kath, J., Mushtaq, S., Henry, R., Adeyinka, A. A., Stone, R., Marcussen, T., and Kouadio, L.: Spatial variability in regional scale drought index insurance viability across Australia's wheat growing regions, Climate Risk Management, 24, 13–29, https://doi.org/10.1016/j.crm.2019.04.002, 2019.

Komendantova, N., Mrzyglocki, R., Mignan, A., Khazai, B., Wenzel, F., Patt, A., and Fleming, K.: Multi-hazard and multi-risk decision-support tools as a part of participatory risk governance: Feedback from civil protection stakeholders, International Journal of Disaster Risk Reduction, 8, 50–67, https://doi.org/10.1016/j.ijdrr.2013.12.006, 2014.

Kraehnert, K., Osberghaus, D., Hott, C., Habtemariam, L. T., Wätzold, F., Hecker, L. P., and Fluhrer, S.: Insurance Against Extreme Weather Events: An Overview, Review of Economics, 72, 71–95, https://doi.org/10.1515/roe-2021-0024, 2021.

Leblois, A., Quirion, P., and Sultan, B.: Price vs. weather shock hedging for cash crops: Ex ante evaluation for cotton producers in Cameroon, Ecological Economics, 101, 67–80, https://doi.org/10.1016/j.ecolecon.2014.02.021, 2014.

Li, P., Xiao, C., Feng, Z., Li, W., and Zhang, X.: Occurrence frequencies and regional variations in Visible Infrared Imaging Radiometer Suite (VIIRS) global active fires, Global Change Biology, 26, 2970–2987, https://doi.org/10.1111/gcb.15034, 2020.

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P., Clarke, M., Devereaux, P. J., Kleijnen, J., and Moher, D.: The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration, Journal of clinical epidemiology, 62, e1–e34, 2009.

Liu, W., Sun, W., Huang, J., Wen, H., and Huang, R.: Excessive Rainfall Is the Key Meteorological Limiting Factor for Winter Wheat Yield in the Middle and Lower Reaches of the Yangtze River, Agronomy, 12, 50, https://doi.org/10.3390/agronomy12010050, 2021.

Lyon, B. and Barnston, A. G.: ENSO and the Spatial Extent of Interannual Precipitation Extremes in Tropical Land Areas, Journal of Climate, 18, 5095–5109, https://doi.org/10.1175/JCLI3598.1, 2005.

Lyubchich, V., Newlands, N. K., Ghahari, A., Mahdi, T., and Gel, Y. R.: Insurance risk assessment in the face of climate change: Integrating data science and statistics, WIREs Computational Statistics, 11, https://doi.org/10.1002/wics.1462, 2019.

Matsumoto, T. and Yamada, Y.: Simultaneous hedging strategy for price and volume risks in electricity businesses using energy and weather derivatives, Energy Economics, 95, https://doi.org/10.1016/j.eneco.2021.105101, 2021.

Mckee, T. B., Doesken, N. J., and Kleist, J.: THE RELATIONSHIP OF DROUGHT FREQUENCY AND DURATION TO TIME SCALES, in: Eighth Conference on Applied Climatology, 1993.

Miranda, M. J.: Area-Yield Crop Insurance Reconsidered, American Journal of Agricultural Economics, 73, 233–242, https://doi.org/10.2307/1242708, 1991.

Mohor, G. S. and Mendiondo, E. M.: Economic indicators of hydrologic drought insurance under water demand and climate change scenarios in a Brazilian context, Ecological Economics, 140, 66–78, https://doi.org/10.1016/j.ecolecon.2017.04.014, 2017.

Mortensen, E. and Block, P.: ENSO Index-Based Insurance for Agricultural Protection in Southern Peru, Geosciences, 8, 64, https://doi.org/10.3390/geosciences8020064, 2018.

Müller, A. and Grandi, M.: Weather derivatives: a risk management tool for weather-sensitive industries, The Geneva Papers on Risk and Insurance. Issues and Practice, 25, 273–287, 2000.

Mußhoff, O., Hirschauer, N., Grüner, S., and Pielsticker, S.: Bounded rationality and the adoption of weather index insurance, Agricultural Finance Review, 78, 116–134, https://doi.org/10.1108/AFR-02-2017-0008, 2018.

Nelsen, R. B.: An Introduction to Copulas, Springer Series in Statistics, Springer New York, New York, NY, https://doi.org/10.1007/0-387-28678-0, 2006.

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

Olya, H. G. and Alipour, H.: Risk assessment of precipitation and the tourism climate index, Tourism Management, 50, 73–80, https://doi.org/10.1016/j.tourman.2015.01.010, 2015.

Paul, C., Hanley, N., Meyer, S. T., Fürst, C., Weisser, W. W., and Knoke, T.: On the functional relationship between biodiversity and economic value, Science Advances, 6, https://doi.org/10.1126/sciadv.aax7712, 2020.

Pislyakov, V. and Shukshina, E.: Measuring excellence in Russia: Highly cited papers, leading institutions, patterns of national and international collaboration, Journal of the Association for Information Science and Technology, 65, 2321–2330, https://doi.org/10.1002/asi.23093, 2014.

Raucci, G. L., Lanna, R., da Silveira, F., and Capitani, D. H. D.: Development of weather derivatives: evidence from the Brazilian soybean market, Italian Review of Agricultural Economics, 74, 17–28, 2019.

Re, S.: World insurance: Riding out the 2020 pandemic storm, Sigma, 4, https://www.swissre.com/dam/jcr:05ba8605-48d3-40b6-bb79-b891cbd11c36/sigma4_2020_en.pdf, 2020.

Re, S.: World insurance: the recovery gains pace, Sigma, 3, https://www.swissre.com/dam/jcr:ca792993-80ce-49d7-9e4f-7e298e399815/swiss-re-institute-sigma-3-2021-en.pdf, 2021.

Ricome, A., Affholder, F., Gérard, F., Muller, B., Poeydebat, C., Quirion, P., and Sall, M.: Are subsidies to weather-index insurance the best use of public funds? A bio-economic farm model applied to the Senegalese groundnut basin, Agricultural Systems, 156, 149–176, 2017.

RIGHETTO, A., Mendiondo, E., and RIGHETTO, J.: Modelo de Seguro para Riscos Hidrológicos, Revista Brasileira de Recursos Hídricos, 12, 107–113, https://doi.org/10.21168/rbrh.v12n2.p107-113, 2007.

Rodríguez, Y. E., Pérez-Uribe, M. A., and Contreras, J.: Wind put barrier options pricing based on the Nordix index, Energies, 14, 1177, 2021.

Rosenzweig, C. and Parry, M. L.: Potential impact of climate change on world food supply, Nature, 367, 133–138, https://doi.org/10.1038/367133a0, 1994.

Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T. L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S., and Imeson, A.: Attributing physical and biological impacts to anthropogenic climate change, Nature, 453, 353–357, https://doi.org/10.1038/nature06937, 2008.

Sacchelli, S., Cipollaro, M., and Fabbrizzi, S.: A GIS-based model for multiscale forest insurance analysis: The Italian case study, Forest Policy and Economics, 92, 106–118, https://doi.org/10.1016/j.forpol.2018.04.011, 2018.

Salgueiro, A. M.: Weather index-based insurance as a meteorological risk management alternative in viticulture, Wine Economics and Policy, 8, 114–126, 2019.

Sant, D. T.: Estimating Expected Losses in Auto Insurance, The Journal of Risk and Insurance, 47, 133, https://doi.org/10.2307/252686, 1980.

Sarris, A.: Weather index insurance for agricultural development: Introduction and overview, Agricultural Economics (United Kingdom), 44, 381–384, https://doi.org/10.1111/agec.12022, 2013.

Scopus: What is Scopus about?, https://service.elsevier.com/app/answers/detail/a_id/15100/supporthub/scopus/, 2022.

Sekhri, S., Kumar, P., Fürst, C., and Pandey, R.: Mountain specific multi-hazard risk management framework (MSMRMF): Assessment and mitigation of multi-hazard and climate change risk in the Indian Himalayan Region, Ecological Indicators, 118, 106 700, https://doi.org/10.1016/j.ecolind.2020.106700, 2020.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture–climate interactions in a changing climate: A review, Earth-Science Reviews, 99, 125–161, https://doi.org/10.1016/J.EARSCIREV.2010.02.004, 2010.

Shirsath, P., Vyas, S., Aggarwal, P., and Rao, K. N.: Designing weather index insurance of crops for the increased satisfaction of farmers, industry and the government, Climate Risk Management, 25, 100 189, https://doi.org/10.1016/j.crm.2019.100189, 2019.

Skees, J. R.: Challenges for use of index-based weather insurance in lower income countries, Agricultural Finance Review, 68, 197–217, https://doi.org/10.1108/00214660880001226, 2008.

Smith, A. B. and Matthews, J. L.: Quantifying uncertainty and variable sensitivity within the US billion-dollar weather and climate disaster cost estimates, Natural Hazards, 77, 1829–1851, https://doi.org/10.1007/S11069-015-1678-X/FIGURES/8, 2015.

Spangenberg, J. H. and Settele, J.: Precisely incorrect? Monetising the value of ecosystem services, Ecological Complexity, 7, 327–337, https://doi.org/10.1016/j.ecocom.2010.04.007, 2010.

Stephan, J. and Brix, A.: Weather Derivative Valuation?: The Meteorological, Statistical, Financial a., 373, https://www.amazon.com.br/Weather-Derivative-Valuation-Meteorological-Mathematical/dp/0521843715, 2005.

Štulec, I., Petljak, K., and Naletina, D.: Weather impact on retail sales: How can weather derivatives help with adverse weather deviations?, Journal of Retailing and Consumer Services, 49, 1–10, 2019.

Tilloy, A., Malamud, B. D., Winter, H., and Joly-Laugel, A.: A review of quantification methodologies for multi-hazard interrelationships, Earth-Science Reviews, 196, 102 881, https://doi.org/10.1016/J.EARSCIREV.2019.102881, 2019.

Turvey, C., Shee, A., and Marr, A.: Addressing fractional dimensionality in the application of weather index insurance and climate risk financing in agricultural development: A dynamic triggering approach, Weather, Climate, and Society, 11, 901–915, https://doi.org/10.1175/WCAS-D-19-0014.1, 2019.

UNEP, F.: Principles for sustainable insurance, 2012.

Vasseur, D. A., DeLong, J. P., Gilbert, B., Greig, H. S., Harley, C. D. G., McCann, K. S., Savage, V., Tunney, T. D., and O'Connor, M. I.: Increased temperature variation poses a greater risk to species than climate warming, Proceedings of the Royal Society B: Biological Sciences, 281, 20132 612, https://doi.org/10.1098/rspb.2013.2612, 2014.

Vicente-Serrano, S. M., López-Moreno, J. I., Gimeno, L., Nieto, R., Morán-Tejeda, E., Lorenzo-Lacruz, J., Beguería, S., and Azorin-Molina, C.: A multiscalar global evaluation of the impact of ENSO on droughts, Journal of Geophysical Research, 116, D20 109, https://doi.org/10.1029/2011JD016039, 2011.

Vroege, W. and Finger, R.: Insuring Weather Risks in European Agriculture [Assurer les risques météorologiques dans l'agriculture européenne], EuroChoices, 19, 54–62, https://doi.org/10.1111/1746-692X.12285, 2020.

Vroege, W., Bucheli, J., Dalhaus, T., Hirschi, M., and Finger, R.: 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, https://doi.org/10.1093/erae/jbab010, 2021.

Wang, S. S.: A Universal Framework for Pricing Financial and Insurance Risks, ASTIN Bulletin, 32, 213–234, https://doi.org/10.2143/AST.32.2.1027, 2002.

Ward, P. and Makhija, S.: New modalities for managing drought risk in rainfed agriculture: Evidence from a discrete choice experiment in Odisha, India, World Development, 107, 163–175, https://doi.org/10.1016/j.worlddev.2018.03.002, 2018.

https://doi.org/10.5194/egusphere-2022-498
Preprint. Discussion started: 7 July 2022

Ward, P., Makhija, S., and Spielman, D.: Drought-tolerant rice, weather index insurance, and comprehensive risk management for smallholders: evidence from a multi-year field experiment in India, Australian Journal of Agricultural and Resource Economics, 64, 421–454, https://doi.org/10.1111/1467-8489.12342, 2020.

Wilhite, D. A. and Glantz, M. H.: Understanding: the drought phenomenon: the role of definitions, Water international, 10, 111–120, 1985.

Yoshida, K., Srisutham, M., Sritumboon, S., Suanburi, D., Janjirauttikul, N., and Suanpaga, W.: Evaluation of economic damages on rice production under extreme climate and agricultural insurance for adaptation measures in Northeast Thailand, Engineering Journal, 23, 451–460, https://doi.org/10.4186/ej.2019.23.6.451, 2019.

Zara, C.: Weather derivatives in the wine industry, International Journal of Wine Business Research, 22, 222–237, https://doi.org/10.1108/17511061011075365, 2010.