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Developing a multi-hazard risk index-based insurance for viticulture under climate change

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Abstract. Climate change is increasing the frequency and severity of environmental hazards (e.g., prolonged drought), and even non-extreme climate events (e.g., a period of slightly warmer temperatures) can lead to extreme impacts when they occur simultaneously with other (non-extreme) events. In viticulture, climate-related hazards (droughts, heatwaves, and frosts) increase the probability of risks (grapes yield and quality reduction), ultimately threatening the economic sustainability of viticulturists. In response and as a theoretical framework, this study develops a multi-hazard risk index-based insurance product for viticulture, enabling insurers and viticulturists to manage complex, interacting climate-related hazards. The product is structured through three interconnected modules. The hazard module identifies key climate-related hazards and their combined impact through multi-criteria approaches, developing a multi-hazard risk index, which then establishes critical thresholds (trigger for payouts and exit from payouts in index-based insurance products). The vulnerability module quantifies potential economic losses due to the identified hazards using a mathematical function (regressions) providing a tick value, which refers to the monetary value associated with a unit of loss in index-based insurance products. The financial module integrates hazard and vulnerability outputs into an insurance mechanism, with the premium price paid by viticulturists to the insurers for the insurance coverage calculation at its core, employing the Black-Scholes method for premium pricing. Offering a transparent and efficient risk transfer mechanism associated with a localized multi-hazard index, this research empowers insurers and viticulturists in the specific region to better manage financial risks associated with climate-related hazards and to enhance the resilience of the viticulture sector.

1. Introduction

Viticulture, the production of grapevines, covers over 7.3 million hectares globally, making it one of the most important agricultural and economic sectors [OIV]. Viticulture is highly sensitive to climate, where temperature and precipitation regulate all key phenological stages from budburst to ripening and harvest, highlighting its vulnerability to climate change. Any variations in these environmental factors mean the sector faces increasing risk and uncertainty regarding yield stability, grape quality, and long-term viability, especially in regions with significant economic, cultural, and social connections to viticulture [1]. Furthermore, beyond just temperature and precipitation changes, more frequent climate events like droughts, heatwaves, and frosts are also impacting vine yields and health [2]. Moreover, the growing overlap of events even not-extreme, such as heatwaves coinciding with drought or hail followed by high humidity, underscores the increasing frequency and complexity of climate-related hazards in viticulture [3].

Rising climate-related hazards and the consequent risks highlight the urgent need for innovative risk management tools. Insurance is one of the most critical financial instruments for mitigating agricultural risk, enabling farmers to safeguard against losses and maintain stability. However, traditional indemnity-based models are often not well-suited to agriculture due to the systemic nature of climate-related hazards, the challenge of verifying individual losses, and the high costs of claim assessment [4-5]. Index-based insurance has emerged as an alternative. Instead of assessing physical damage, payouts are triggered by predefined climate indices such as cumulative precipitation or temperature deviations, allowing for faster and more objective compensation. However, early versions of such insurance schemes typically focused on a single hazard, such as precipitation deficit, but growing evidence suggests that mono-risk triggers fail to reflect the interlinked nature of climate-related hazards in complex cropping systems like viticulture [6], especially considering complex climate-related hazards such as droughts, which are prolonged periods of significantly below-average precipitation, often exacerbated by rising temperatures. Therefore, recognizing the role of complex climate-related hazards in agricultural vulnerability [IPCC], the focus has shifted toward multi-hazard risk index-based insurance, which accounts for the cumulative effects of various hazards [7].

Understanding multi-climate-related hazards is crucial for comprehensive risk assessment and the development of effective adaptation strategies. This paper proposes a novel theoretical framework for multi-hazard risk index-based insurance in viticulture, integrating bioclimatic indices that are more representative of vine-specific climatic sensitivity into index-based insurance products. Section 2 introduces single-hazard risk index-based insurance, explaining simpler insurance models triggered by a single climate hazard and their limitations. Section 3 presents bioclimatic indices in viticulture, delving into the specific climate factors critical for grapevine growth and defining relevant bioclimatic indices. Section 4 introduces multi-hazard risk index-based insurance, detailing the integration of multiple bioclimatic indices into a comprehensive index and the methodology for combining them to trigger payouts effectively. Section 5, conclusion and future implications, summarizes the key contributions and suggests directions for further research.

2. Single-hazard index-based insurance

To address the economic risks posed by climate change, effective risk management tools are essential. Insurance offers a way to transfer financial risk and stabilize the incomes of farmers facing climate-induced losses [4]. However, traditional indemnity-based insurance has limitations in agriculture, where risks are often systemic and highly correlated, making assessment and compensation complex and costly [5]. As a result, there is increasing interest in alternative mechanisms, most notably, index-based insurance, which provides faster, more transparent coverage against widespread losses [8]. Index-based insurance uses predefined index values, highly correlated with losses, to trigger payouts and determine their magnitude, rather than assessing individual damage [9]. This approach monitors hazards through specific variables like precipitation and temperature, for a particular sector. When the monitored index value exceeds predefined limits, insured entities receive compensation regardless of actual physical damage [10]. Therefore, payouts are trigged based on these predetermined indicators, enabling objective and timely claim settlements and reducing administrative burdens. For instance, if precipitation falls below a set threshold, an indemnity is paid based on a pre-agreed amount per millimetre of precipitation [9]. However, While index-based insurance helps mitigate adverse selection and moral hazards in traditional models, it introduces basis risk, the risk that payouts do not align with actual losses. Consequently, a farmer might receive a payout despite no loss or receive nothing despite experiencing damage [8]. Therefore, accurate index selection and calculation is a critical step in designing index-based insurance products to reduce the basis risk.

3. Bioclimatic indices in viticulture

Bioclimatic indices are biologically meaningful variables derived from temperature and precipitation values [World Climate]. Serving as essential tools in understanding the interactions between climate and agricultural production, these indices are widely used in agriculture to assess climatic suitability and stress factors affecting crop growth. For example, in viticulture, bioclimatic indices offer significant insights into the suitability of a region for grape cultivation, the selection and adaptation of grape varieties, and vineyard management practices across various time scales [11]. The International Organisation of Vine and Wine (OIV) classified the bioclimatic indices for viticulture into three broad categories: (1) the thermal indices or temperature-based indices that make the temperature effects quantifiable, (2) the hydrological indices or precipitation-based indices that quantify water balance and dryness conditions, and (3) the extreme event indices or compounded events indices to evaluate risks of frost, heatwaves, droughts, etc. [OIV]. A sample list of bioclimatic indices frequently used in viticulture [11] includes the mean temperature during vegetation period, Heliothermic Huglin index, Winkler degree days, biologically effective degree days, cool night index, growing season precipitation index, spring rain index, etc. However, these indices are primarily calculated based on a single input variable (temperature or precipitation). More complex climatic events exist, such as frost during the growing season, heatwave magnitude index, vapor pressure deficit magnitude index, and number of high wind speed events, etc. [12].

4. Multi-hazard index-based insurance

The increasing frequency and severity of climate-related hazards, including droughts, heatwaves, and extreme precipitation [13], demand for advanced risk transfer mechanisms addressing complex hazards [14]. Climate events that are not extreme can nevertheless lead to extreme impacts when occurring simultaneously with other (non-extreme) events. Adopting a single-hazard approach would risk underestimating the potential risk a certain region faces [15]. Hence, there is a general agreement that disaster risk reduction needs to move from single- to multi-hazard scenarios. A multi-hazard approach can help policymakers and investors decide where to channel money and attention, thereby making development efforts and hazard response risk-informed and more efficient. This study advances a multi-hazard risk index-based insurance framework, systematically integrating climatic risks with economic impacts through three sequential modules: hazard characterization, vulnerability quantification, and financial structuring. By transforming physical hazards into actionable financial instruments, the framework bridges the gap between climate science and risk management, offering a scalable solution for sectors like viticulture that face multifaceted climate exposures [6,10,15]. Figure 1 summarize the values that can be estimated through the three interconnected modules.

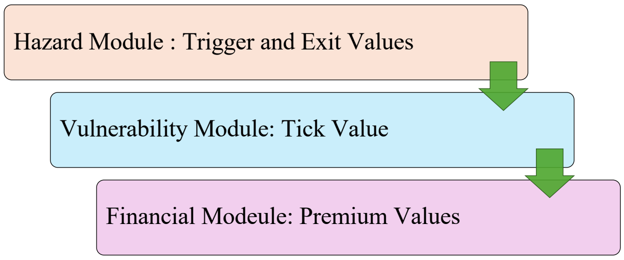

Figure 1. Premium calculation through the three interconnected modules.

4.1. Hazard Module: Climate-related risk detector

The hazard module establishes the scientific foundation by constructing a multi-hazard risk index that synthesizes diverse climate threats into a unified metric. Using bioclimatic indicators, the index quantifies hazard intensity while minimizing basis risk through statistical calibration. Hazard weighting employs hybrid methodologies, combining expert judgment to prioritize locally relevant risks and to derive empirical relationships between hazard magnitude and agricultural outcomes. The aggregated risk score is partitioned into discrete severity tiers, low, moderate, and high, using percentile-based thresholds (trigger and exit) aligned with historical loss data. These thresholds later serve as triggers for insurance payouts, ensuring the index responds to economically meaningful deviations from baseline conditions.

4.2. Vulnerability Module: Loss estimation

The vulnerability module translates hazard magnitudes into economic losses, focusing on direct financial impacts rather than broader socio-environmental factors. A deterministic relationship links the multi-hazard index values to daily production losses, derived from input-cost analyses and historical damage records. This daily loss value functions as the tick in the payout function, ensuring compensation scales linearly with both hazard duration and intensity. The module’s output is a loss curve mapping index values to monetary damages that directly informs the financial module’s actuarial calculations.

4.3. Financial Module: Premium evaluation

The financial module designs the insurance product by pricing risk and defining contract parameters. To achieve this, Black-Scholes method [16] is a potential technique. It was initially developed in 1973 for estimating financial option prices and later applied to weather derivatives. The Black-Scholes approach enables premium computation based on the probability distribution of the index's terminal value relative to critical thresholds. This market-consistent and mathematically rigorous pricing mechanism enhances transparency and efficiency for the proposed multi-hazard risk insurance model for viticulture, aligning with established practices in environmental finance and agri-risk management.

5. Conclusion and future implications

This study establishes a robust theoretical foundation for multi-hazard index-based insurance products by integrating climate science, economic analysis, and financial engineering. The proposed three-module framework provides insurers with a systematic methodology to develop parametric products that effectively address complex climate risks. The hazard module's scientific approach to index construction ensures objective risk assessment, while the vulnerability module's economic loss quantification maintains alignment between payouts and actual damages. The financial module offers practical tools for sustainable premium calculation and risk transfer mechanisms. For insurance providers, this framework represents a significant advancement over traditional indemnity-based products by reducing moral hazard, minimizing administrative costs through automated triggers, and enhancing transparency for all stakeholders. The methodology's flexibility allows adaptation across different agricultural sectors and geographic regions, making it particularly valuable in an era of increasing climate volatility.

Future studies should focus on enhancing the framework's practical implementation and expanding its theoretical foundations. Research into behavioural economic factors influencing product adoption could optimize design features and communication strategies to increase uptake among target populations. Comparative studies across different agro-climatic zones would provide valuable insights for regional customization of indices and thresholds. The potential integration of emerging technologies such as IoT sensors and blockchain-based smart contracts warrants investigation to improve accuracy and transparency in index calculation. Collaborative research with policymakers should examine regulatory adaptations needed to facilitate widespread adoption, particularly in developing economies where climate vulnerability is most acute. Longitudinal studies assessing the long-term performance of such products under various climate scenarios will be essential for continuous improvement and adaptation of the framework.

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