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Research on Meteorological Index Insurance for Tea Frost Damage in Mingshan, China

Meng Yuan[1,2,3], Xiaoshuang Li[1], Wenbo Gao[4*], Xin Gao[2,5], Yaping Wu[2,5]

[1]Sichuan Rural Economic Information Center, Chengdu, China
[2]Southwest Sichuan (Ya'an) Rainstorm Laboratory, Ya'an, China
[3]Sichuan Weather Modification Center, Chengdu, China
[4]Sichuan Academy of Agricultural Sciences, Chengdu, China
[5]Ya'an Meteorological Bureau, Ya'an, China
Email: *532400153@qq.com

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Abstract

Tea is one of the most important economic crops in China. Mingshan in Sichuan Province is one of the earliest regions with documented history of tea cultivation, consumption, and trade, possessing high representativeness. Spring low-temperature frost represents the primary meteorological disaster threatening tea production in Mingshan District, Ya'an City, Sichuan Province, severely affecting both spring tea yield and quality while causing substantial income losses for tea farmers. Based on meteorological observation data and actual tea production conditions in Mingshan District, this study systematically analyzed the characteristics of tea frost damage and the relationship between extreme daily minimum temperature and tea yield reduction rate. The Frost Integrated Index (FII) for Mingshan District was constructed, an index-loss model was established, and a tea frost weather index insurance product was designed. The results indicate that: 1) During the tea growing season, frost damage in this region occurs predominantly between February-April, with March exhibiting the highest frequency of extreme low-temperature events; 2) The frost integrated index, with extreme daily minimum temperature as the core indicator combined with date weighting coefficient and elevation correction coefficient, can effectively characterize the impact of different frost grades on tea production; 3) The index-loss model indicates that when the extreme minimum temperature drops to a level where the Frost Damage Integrated Index (FII) exceeds 25, the comprehensive economic loss rate of tea can reach over 75%; 4) The designed insurance product adopts an FII value of ≥5 as the payout trigger threshold, with six indemnity grades established. The weather index insurance operates under a "pay-upon-trigger" mechanism, which eliminates the need for on-site survey and loss adjustment. This approach can effectively reduce moral hazard, adverse selection, and claims costs while improving claims efficiency. This study provides technical support for tea industry risk management in Mingshan District and offers a reference for the refined design of weather index insurance products in tea-producing regions of Southwest China.

Keywords

Tea Frost Damage, Weather Index Insurance, Mingshan District, Extreme Minimum Temperature

1. Introduction

Mingshan District, Ya'an City, Sichuan Province, China, is documented as the earliest site of artificial tea cultivation, renowned as the "Hometown of Chinese Tea Culture." Tea represents the pillar industry of Mingshan District, with a total tea garden area of approximately 392,000 mu and a comprehensive output value exceeding 10 billion yuan. Tea income accounts for more than 60% of farmers' per capita disposable income [1].

However, Mingshan is characterized by a subtropical humid monsoon climate, where spring "late cold spells" (late spring cold snap) frequently occur, posing a significant threat to spring tea production and quality. During early spring, tea shoots enter the germination period with thinner cell walls and elevated free water content, resulting in reduced cold resistance. When temperatures decline, intercellular water in tea buds freezes, potentially causing growth cessation, plant mortality, delayed harvest periods, and reductions in both tea yield and quality [2].

Traditional agricultural insurance adopts a "loss assessment" model, which suffers from moral hazard, high survey and loss assessment costs, and difficulties in precise damage evaluation [3]. Weather Index Insurance (WII) uses objective meteorological data as the basis for payout, employing a "trigger-based payout" mechanism that eliminates the need for on-site surveys and loss assessments, thereby reducing labor costs and effectively overcoming the deficiencies of traditional agricultural insurance. In recent years, WII has been widely applied [4].

Overseas research on tea meteorology started relatively early. Barnett *et al.* [5] systematically demonstrated the advantages and applicability of weather index insurance in agricultural risk transfer. Perera *et al.* [6] further designed a complete weather index based insurance scheme for mitigating spring frost risks in tea plantations. Gunaratne *et al.* [7] analyzed the adverse impacts of early spring low temperature events on tea bud burst in Sri Lankan tea growing regions. Lou Weiping's team [8] pioneered the pilot program for tea low-temperature weather index insurance in Zhejiang, determining daily minimum temperature $\leq 0˚C$ as the trigger threshold. Liu Ruina *et al.* [9] took Huangshan Maofeng as the research object and, based on ANUSPLIN interpolation and GIS technology, constructed a terrain-refined pure premium rate determination model for tea frost weather index insurance. Huang Chuanrong *et al.* [10] constructed multi-grade meteorological trigger indicators and yield reduction classification models for tea cold and frost damage in Fujian Province, achieving risk zoning and differentiated premium rate determination with graded claims. Wang Chunhui *et al.* [11] proposed methods for establishing trigger conditions and payout standards based on tea cold and frost damage weather index insurance design. For the Sichuan tea region, Peng Jun *et al.* [12] analyzed the climatic suitability of tea in Ya'an Mengding Mountain, identifying spring low temperatures during February-April each year as the key limiting factor affecting Ya'an spring tea yield.

However, research on tea frost index-loss models and insurance product design specifically targeting Mingshan District, an important tea-producing region in Southwest China, remains relatively scarce. Therefore, this study takes Mingshan District as the research object, analyzing the relationship between extreme daily minimum temperature and tea yield reduction, constructing a tea frost index-loss model, and designing a tea frost weather index insurance product for this region, with the aim of providing theoretical basis and technical support for the promotion of tea weather index insurance in Mingshan District and the broader Southwest China tea region.

2. Data and Sources

Meteorological data were obtained from the national automatic weather station in Mingshan District for the period 2004-2023, including hourly air temperature and daily extreme minimum temperature. Data on tea cultivation area and yield for the main tea-producing regions of Mingshan District were sourced from the Ya'an Meteorological Bureau, Ya'an Statistical Yearbook, annual national economic and social development statistical bulletins published by the Mingshan District Statistics Bureau, and publicly available government work reports and documents from the Mingshan District Government. All yield datasets adopted in this paper are original county-level statistical data of Mingshan District, Sichuan Province. The trend yield method is applied to separate meteorological yields during yield calculation for constructing the tea frost index loss model.

3. Overview of the Study Area

Mingshan District is located on the western margin of the Sichuan Basin, in the eastern part of Ya'an City, with a total area of 614.27 km^2. The terrain consists primarily of low mountains and hills, with tea gardens mainly distributed on hilly slopes at elevations of 600 - 1000 m. The region belongs to the subtropical humid monsoon climate, with an annual average temperature of 15.4˚C, annual precipitation of 1500 mm, and annual sunshine duration of 1039 hours [13]. The area is characterized by high humidity, abundant fog, and relatively low sunshine, with suitable soil pH conditions, making the natural environment highly favorable for tea cultivation. Local tea plants exhibit rapid early-spring germination, with tender buds and leaves possessing weak cold resistance, rendering them highly susceptible to frost damage from early-spring temperature declines.

Mingshan District is recognized as "China's Top Green Tea County," possessing two major regional public brands: Mengding Mountain Tea and Ya'an Zangcha. The main cultivated varieties include Fuxuan No. 9, Mingshan Baihao 131, and Fuding Dabaicha [1]. The spring tea harvest period generally spans from late February to mid-April, with the peak harvest occurring from mid-March to early April, during which tea buds are at their most tender and most sensitive to low-temperature frost damage [14].

4. Analysis of Tea Frost Damage Characteristics in Mingshan District

4.1. Temporal and Spatial Distribution Characteristics of Spring Low Temperatures

Based on observational data from the Mingshan National Meteorological Reference Station, the mean extreme minimum temperature during February-April over the 20-year period spanning 2004-2023 was 0.14˚C in Mingshan District, with an absolute minimum of −2.40˚C (recorded in 2008) and a standard deviation of 1.40˚C, indicating considerable interannual variability in late-winter to early-spring low temperatures. The characteristics of the extreme minimum temperature from February to April in Mingshan District during the period 2004-2023 are shown in **Table 1**.

Table 1. Statistical characteristics of extreme minimum temperature between February and April in Mingshan District (2004-2023).

Statistic	Value	Remarks
Mean	0.14˚C	20-year average
Minimum	−2.40˚C	Recorded on February 2, 2008
Standard Deviation	1.40˚C	High interannual variability

From a temporal distribution perspective, March exhibited the highest frequency of extreme low-temperature events between February and April, accounting for 68.5% of the time period's low-temperature occurrences, followed by February (21.3%) and April (10.2%).

The heatmap of the monthly extreme minimum temperatures in Mingshan District from 2004 to 2023 is shown in **Figure 1**. The lowest extreme minimum temperature over the past 20 years was recorded on 25 January 2016 (−4.4˚C). Although January temperatures are generally low, tea plants during this period are in dormancy. For tea plants in deep dormancy, the impact of low-temperature freezing injury is less severe than that on plants in the budding stage. Given that the plucking of Mingshan spring tea and its large-scale harvesting typically occur from early February to early March, when rising temperatures induce the budbreak stage—a critical period coinciding with the onset of spring tea harvesting—tea plants become more vulnerable to low-temperature frost damage. This interval therefore constitutes the key focus of our study.

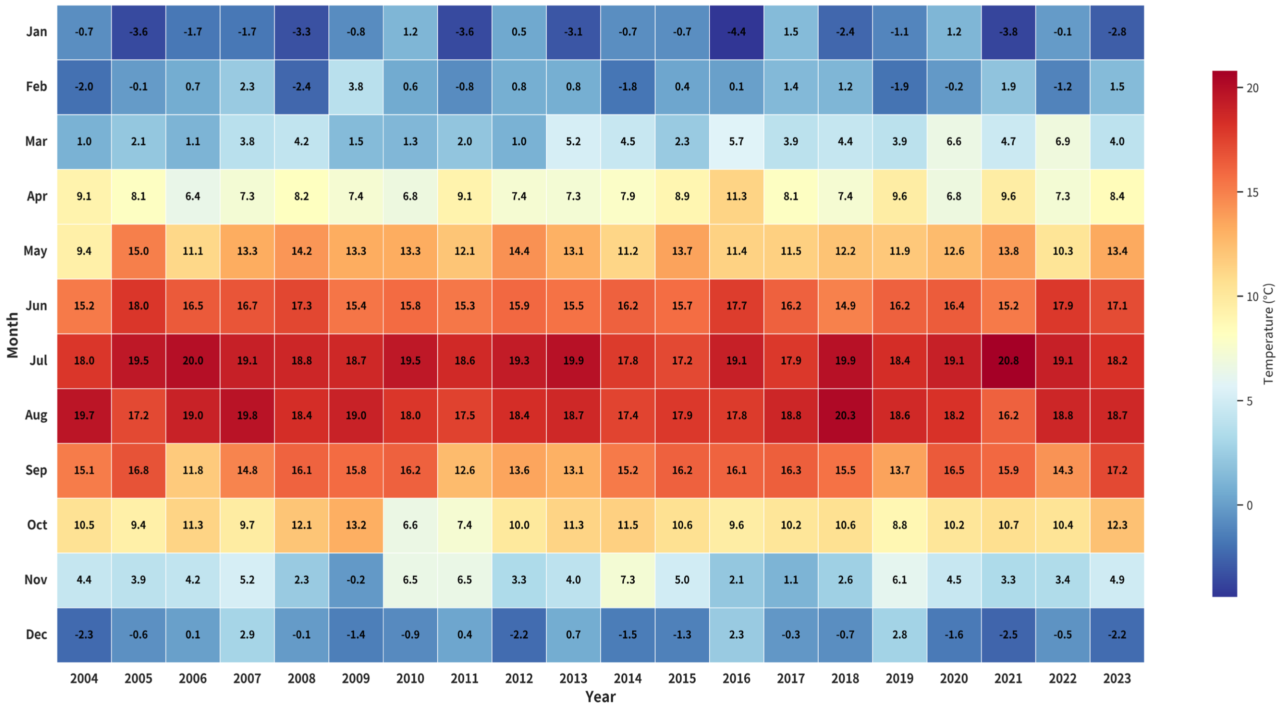

Figure 1. Heatmap of monthly extreme minimum temperature of Mingshan (2004-2023).

4.2. Mechanism of Tea Frost Damage

Newly emerged tea buds and leaves possess high water content and fragile cellular structures, with relatively poor low-temperature tolerance [2]. When ambient temperatures decline, intracellular water in leaf cells freezes, damaging the plant cell membrane structure and causing bud and leaf wilting, browning, desiccation, and abscission. Frost damage to tea plants is irreversible; the lower the temperature and the longer the duration of temperature decline, the more severe the yield losses in tea gardens [15].

4.3. Characteristics of Frost Disasters in Mingshan District

Through field investigations at tea cultivation bases and fresh leaf trading markets in Mingshan District, the high-risk periods and characteristics of spring tea frost damage are summarized in **Table 2**.

Based on field investigations, the tea frost disasters in this region exhibit the following characteristics:

First, concentrated occurrence timing. Frost damage is concentrated primarily from late February to early April each year, overlapping with the high-value growth period of tea.

Second, strong suddenness and uneven spatial distribution. Cold air accumulates in valley lowlands, where frost damage is most severe; slopes and elevated tea gardens experience relatively higher temperatures, but frost severity can vary significantly even at different positions on the same slope.

Table 2. High-risk periods for spring tea frost damage in Mingshan District.

Period	Risk Level	Cause
Late Feb-early Mar	High	Bud break begins; cold resistance declines sharply.
Early March	High	Harvest onset; young shoots highly susceptible to frost.
Mid-late March	Moderate	Cold tolerance partially restored during shoot growth.
"Late spring cold snap"	High	Rapid cooling after warming; insufficient physiological adjustment.

Third, pronounced interannual variability. The intensity of cold air activity varies considerably among years, with alternating severe and mild frost years, resulting in significant insurance risk fluctuations.

5. Construction of Tea Frost Index-Loss Model

5.1. Construction of Frost Damage Integrated Index

5.1.1. Selection of Core Indicators

Considering the disaster-causing mechanism of tea frost damage, climatic characteristics of Mingshan District, and data availability, extreme daily minimum temperature was selected as the core indicator of the frost damage index. This indicator offers advantages of strong objectivity, standardized observation, and good spatial comparability, and exhibits a significant quantitative relationship with the degree of tea frost damage [16].

5.1.2. Frost Damage Grade Classification

Referring to the classification design methods of weather index insurance for tea cold injury and frost damage in other provinces of China [10], and combining the climatic characteristics of Mingshan District with the cold resistance of tea plants, the frost damage was classified into the following six grades through expert consultation, as shown in **Table 3**:

Table 3. Frost damage grade classification.

Frost Damage Grade	Extreme Minimum Temperature (˚C)	Frost Damage Index I	Damage Description
Grade 0	$T > 2$	0	Slight impact
Grade I	$0 < T \leq 2$	1	Marginal buds and leaves slightly frozen; yield impact < 5%
Grade II	$-1 < T \leq 0$	2	Surface buds and leaves frozen; partial growth cessation
Grade III	$-2 < T \leq -1$	4	Majority of new buds frozen; harvesting delayed by 3 - 5 days

Continued

Grade IV	−3 < T ≤ −2	7	Large-area freezing injury; yield reduction > 20%
Grade V	T ≤ −3	10	Severe frost damage; risk of total crop failure

5.1.3. Date Weighting Coefficient

As the spring tea harvesting period approaches, the tea buds gradually become more tender and their cold resistance correspondingly declines. Under identical low-temperature conditions, the resulting losses become more pronounced. Therefore, in consideration of local characteristics and expert consultation results, a date weighting coefficient (Wd) was introduced to reflect the differences in vulnerability across different harvesting periods, as shown in **Table 4** [17].

Table 4. Seasonal periods and temporal weight coefficients (Wd).

Growth Stage	Date Range	Weight Coefficient (Wd)
Budding stage	February 1-February 13	0.6
Initial picking stage	February 14-March 10	1.0
Full picking stage	March 11-April 10	1.1
Late picking stage	April 11-April 30	0.7

5.1.4. Elevation Correction Coefficient

The tea gardens in Mingshan District exhibit significant variations in altitude, with a vertical temperature lapse rate of approximately 0.6˚C per 100 meters. To reflect the impact of altitude on frost risk, and based on local conditions as well as expert consultation results, we introduced an altitude correction coefficient (Wh), as shown in **Table 5** [18]:

Table 5. Correction coefficients (Wh) based on elevation ranges.

Elevation Range	Correction Coefficient (Wh)	Description
H < 700 m	1.0	Major low-elevation production area
700 ≤ h < 900 m	1.2	Mid-elevation zone with relatively high risk
900 ≤ h < 1200 m	1.3	High-elevation zone with high risk
H ≥ 1200 m	1.5	Very high-elevation zone with extremely high risk

5.1.5. Frost Damage Integrated Index Model

Integrating the above indicators, the Frost Damage Integrated Index (FII) for Mingshan District was constructed:

$$FII = \sum_{i=1}^{n} I_i \times W_{d_i} \times W_{h_i}$$

where: FII is the frost damage integrated index; I_i is the frost damage index of the i-th frost event; W_d is the date weighting coefficient; W_h is the elevation correction coefficient; and n is the number of frost events during the insurance period.

A numerical example is provided herein. For a tea garden located at an altitude of 740 m that experiences a low temperature of −1.5˚C on 10 March, the calculation steps for the Frost Damage Integrated Index (FII) are as follows:

① $T = -1.5˚\text{C} \rightarrow I = 4$ (Frost damage Grade III)

② 10 March falls within the initial harvesting period → $W_d = 1.0$

③ Altitude of 740 m → $W_h = 1.3$

④ $FII = 4 \times 1.0 \times 1.3 = 5.2$

5.2. Construction of Index-Loss Model

5.2.1. Yield Reduction Rate Calculation

The trend yield method was employed to separate meteorological yield, and the tea yield reduction rate (Y) was calculated [19]:

$$Y = \left(S_t - S\right)/S_t \times 100\%$$

where: Y is the yield reduction rate (%); S_t is the trend yield (kg/hm^2); and S is the actual yield (kg/hm^2). The trend yield was calculated using the 5-year moving average method.

5.2.2. Model Fitting

Based on tea yield data and meteorological data from Mingshan District for 2014-2023, the relationship model between the frost damage integrated index (FII) and yield reduction rate (Y) was established. Through regression analysis, the following index-loss model was obtained:

$$Y = -2.15 + 3.87 \times FII + 0.062 \times FII^2$$

The model coefficient of determination $R^2 = 0.864$, passing the significance test at $P < 0.05$, indicating a significant quantitative relationship between the frost damage integrated index and tea yield reduction rate.

5.2.3. Disaster Loss Rate Classification

Based on the index-loss model and the empirical findings from the literature on tea quality deterioration coefficients, and combined with field survey results and expert consultation, the comprehensive economic loss rates under different frost damage grades were determined, as shown in **Table 6** [20].

Table 6. Grading of disaster loss rates for freeze injury.

Freeze Injury Grade	Cumulative FII Range	Comprehensive Loss Rate (%)
1	5 ≤ FII < 8	10% - 15%
2	8 ≤ FII < 12	15% - 25%
3	12 ≤ FII < 16	25% - 40%
4	16 ≤ FII < 20	40% - 55%
5	20 ≤ FII < 25	55% - 75%
6	FII ≥ 25	≥75%

6. Tea Frost Weather Index Insurance Design for Mingshan District

6.1. Product Design Principles

The insurance product design adheres to the following principles:

1) Objectivity Principle: Payouts are based on authoritative meteorological observation data, avoiding human interference;

2) Simplicity Principle: A "trigger-based payout" mechanism is adopted to simplify the claims process and reduce operational costs;

3) Fairness Principle: Differentiated premium rates are implemented according to risk differences, reflecting risk-premium matching [21].

6.2. Insurance Elements

The insured subject comprises locally dominant tea cultivars meeting the eligibility criteria, such as Fuxuan 9 and Mingshan Baihao 131. Eligible policyholders include large-scale tea growers, professional cooperatives, tea enterprises, and village collectives. The insurance coverage period spans from February 1 to April 30, encompassing the entire spring tea plucking season. The sum insured is set at 2000 CNY per mu, with a base premium rate of 6%. Consequently, the total premium is 120 CNY per mu.

6.3. Trigger Mechanism and Payout Standards

6.3.1. Claim Trigger Conditions

Based on the daily minimum temperature collected by the Mingshan District meteorological observation station, the daily FII component is calculated by incorporating the date weight coefficient and the altitude weight coefficient as follows: $I \times W_d \times W_h$. The cumulative FII value is obtained by summing all FII components of each freezing injury event occurring during the insurance period. When the FII is greater than or equal to 5, graded compensation shall be paid according to **Table 7**.

6.3.2. Graded Payout Table

The cumulative indemnity payment is capped at 100% of the sum insured (2000 CNY/mu).

A concrete calculation example for the indemnity payment procedure is provided as follows:

1) Collect the daily minimum temperature T from meteorological stations each day, and record the altitude h corresponding to the actual elevation of the tea garden.

2) Calculate the daily Freeze Injury Index (FII) component:

$FII = I$ (freeze injury intensity) $\times$ W_d (date weighting coefficient) $\times$ W_h (altitude weighting coefficient)

3) Sum up all daily FII values within the insurance period to obtain the cumulative FII, then determine the indemnity tier and payment amount in accordance with the tiered compensation table above.

Table 7. Claim payment structure based on cumulative FII.

Grade	Cumulative FII Range	Payout Ratio	Indemnity (CNY/mu)	Corresponding Loss Rate
1	5 ≤ FII < 8	5%	100	10% - 15%
2	8 ≤ FII < 12	12%	240	15% - 25%
3	12 ≤ FII < 16	25%	500	25% - 40%
4	16 ≤ FII < 20	45%	900	40% - 55%
5	20 ≤ FII < 25	70%	1400	55% - 75%
6	FII ≥ 25	100%	2000	≥75%

Illustrative Example: A tea garden sits at an altitude of 850 meters with a covered area of 50 mu; three low-temperature events occurred during the insurance period:

March 5: T = −0.5˚C → FII = 2 × 1.0 × 1.3 = 2.6

March 12: T = −1.8˚C → FII = 4 × 1.1 × 1.3 = 5.72

March 21: T = 0.5˚C → FII = 1 × 1.1 × 1.3 = 1.43

Cumulative FII = 2.6 + 5.72 + 1.43 = 9.75

The cumulative FII falls under the Tier 2 compensation standard.

Total indemnity amount = 240 CNY/mu × 50 mu = 12,000 CNY

7. Conclusions and Discussion

7.1. Main Conclusions

1) During the tea growing period, frost damage in this region mainly occurs from February to April, with the highest frequency of extreme low temperatures occurring in March.

2) A comprehensive frost index, which takes the daily extreme minimum temperature as the core indicator and incorporates a date weight coefficient and an altitude correction coefficient, can effectively characterize the impact of different grades of frost on tea production.

3) A tea frost damage index-loss model was established for the Mingshan District, with a coefficient of determination (R^2) of 0.864. The model shows that when the extreme minimum temperature decreases to the extent that the comprehensive frost index FII exceeds 25, the comprehensive economic loss rate of tea can reach over 75%.

4) A weather index insurance product for tea frost damage in Mingshan District was designed. The insurance product uses a comprehensive frost index (FII) greater than or equal to 5 as the trigger threshold for compensation, sets up six compensation gradients, applies a sum insured of 2000 yuan per mu, and a base premium rate of 6%, thereby achieving refined risk-based pricing.

5) Weather index insurance adopts a "trigger-to-pay" mechanism, which requires no on-site survey or loss assessment. This mechanism can effectively reduce

moral hazard, adverse selection, and claim settlement costs, while improving claim efficiency.

7.2. Discussion

1) The index-loss model constructed in this study is primarily based on historical statistical data. Future research should incorporate controlled experiments and remote sensing monitoring technologies to further improve the physical mechanisms and spatial precision of the model.

2) Basis risk remains the primary challenge facing weather index insurance. Mingshan District features complex terrain with large elevation variations in tea gardens, and insufficient coverage of meteorological monitoring stations often results in inconsistencies between the damage severity of different plots and index trigger outcomes during the same frost event. Existing research has predominantly focused on the county scale, lacking plot-level refined index design [9]. It is recommended to densify the network of tea garden microclimate observation stations in the main tea-producing areas of Mingshan District, combined with UAV remote sensing technology, to achieve integrated "sky-space-ground" monitoring [22].

3) This product is designed as a single-peril index insurance, whose composite index is calculated primarily based on the extreme minimum temperature, which inevitably leads to certain limitations. Crop varieties, cultivation and management practices, pests and diseases, rainfall and other factors may all affect tea yield and quality to varying degrees. Future research can explore incorporating drought, heavy rainfall, hail and other disasters into a comprehensive meteorological index insurance to improve the comprehensiveness of risk protection [23].

4) It is recommended to establish a tea frost damage disaster database, continuously accumulating matched yield and meteorological data, dynamically optimizing model parameters and rate tables, and combining AI technology to achieve iterative upgrading of insurance products.

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Author Contributions

Meng Yuan contributed to data curation, methodology and case-study calculations. Xiaoshuang Li contributed to meteorological data collection and statistical analysis. Wenbo Gao contributed to tea meteorological analysis and model validation. Xin Gao contributed to the analysis of tea-related meteorological disasters and existing challenges. Yaping Wu contributed to policy data collection and formal analysis.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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