Design of a Meteorological Index Insurance Product for Freezing Injury during Flowering Period of *Forsythia suspensa*: A Case Study of Anze

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Abstract Based on the meteorological disaster data of low-temperature freezing damage from the results of the *First National Comprehensive Natural Disaster Risk Survey* in Anze County, and meteorological and freezing damage data in freezing damage events during the flowering period of *Forsythia suspensa* from 2018 to 2025, the critical value of freezing damage during the flowering period of *F. suspensa* in Anze County was determined through analysis and research. Moreover, a freezing damage index was established based on the critical temperature and duration of freezing damage. By utilizing the freezing damage index and yield reduction rate, a disaster damage assessment model was established, and the expected value of historical payout rate was used as the pure insurance premium rate. The design of freezing damage insurance product for *F. suspensa* flowering period was completed, providing technical support for insurance companies to formulate scientific and reasonable pure insurance premium rates for agricultural meteorological disasters and carry out insurance work.

Key words Freezing injury; *Forsythia suspensa*; Meteorological index; Insurance product

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Anze County is located at the southeast foot of Mount Taiyue, with a total area of 1 967 km^2. There are 30 demonstration areas for the cultivation of wild *Forsythia suspensa*, 24 artificial planting areas for *F. suspensa*, and 1 breeding area for high-quality *F. suspensa* in Anze County. The total area of *F. suspensa* is 1 000 km^2, and the annual output is 4 million kg, accounting for one fourth of the total national output. It is known as the "first county for *F. suspensa* production in China". In recent years, Anze County has continuously promoted the development of the *F. suspensa* industry, from extracting *F. suspensa* as a medicine, to *F. suspensa* tea, and then to *F. suspensa* plant beverages. The income from the *F. suspensa* industry has become the main way for Anze farmers to increase their income. But under the background of climate change, the risk of low-temperature freezing damage during the flowering period of *F. suspensa* has increased. From April 7 to 9, 2018, 52.93 hm^2 of *F. suspensa* in Anze County suffered from low-temperature freezing damage, resulting in a yield reduction of over 90%. From April 21 to 25, 2020, *F. suspensa* was severely affected by freezing injury, with the lowest temperature in Liangma Township reaching -9.2 ℃, causing all *F. suspensa* to freeze to death. The low-temperature freezing damage on April 20-21, 2023 caused 26.37 hm^2 of *F. suspensa* to be frozen, resulting in severe direct economic losses. Freezing damage during the flowering period has become a major meteorological disaster affecting the healthy development of the *F. suspensa* industry. As of 2025, the insured area of *F. suspensa* exceeded 33.33 km^2. In 2023, the People's Insurance Company of China (PICC) Property & Casualty Insurance Linfen Branch launched *F. suspensa* planting insurance in Anze County. However, traditional *F. suspensa* insurance products have become increasingly difficult to effectively meet the multi-level needs of risk protection for growers due to high operating costs, information asymmetry, difficulty in surveying and determining losses, and long claims cycles. Therefore, it is necessary to develop insurance product design for freezing damage during the flowering period of *F. suspensa*, and leverage the advantages of meteorological index insurance to improve the level of risk protection.

The goal of designing meteorological index insurance products is to improve the correlation between meteorological index and loss rate, as well as the scientificity of insurance pricing, minimize basis risk during the product design phase, and enhance the rationality and applicability of the product. The meteorological disasters have strong regional characteristics. Currently, domestic scholars Wang Zhenjun[1-2], Liu Yajing[3], and Wang Chunyi[4] have conducted research on the claims index and insurance premium rate of meteorological index insurance for frost damage during the flowering periods of corn, potato, and apple. Yin Dong[5] has explored meteorological index agricultural insurance and its technical issues. Ding Shaoqun[6] has studied the necessity of developing meteorological index insurance and proposed corresponding countermeasures. There are also scholars who have conducted research on meteorological disasters and weather index insurance[7-9]. Few scholars have conducted related research on insurance products for frost damage during the flowering period of *F. suspensa*, especially Anze *F. suspensa*. To this end, a case of freezing damage during the spring flowering periods of *F. suspensa* in Anze County was analyzed. Based on the results of Xing Gang[10], combined with

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claims standards of insurance institutions, a suitable insurance product model for low-temperature freezing damage of *F. suspensa* in Anze was constructed. This could provide technical support for meteorological services of meteorological departments and insurance institutions to develop scientific and reasonable pure insurance premium rates and carry out " insurance + meteorology" work.

1 Data and methods

1.1 Study area The research area is Anze County, Shanxi Province, which governs 6 towns, 66 administrative villages, covers an area of 1 967 km^2, and has an altitude ranging from 750 to 1 500 m. It belongs to the warm temperate continental monsoon climate with distinct four seasons. The average annual sunshine duration is 2 173.8 h, the average annual temperature is 9.7 ℃, the average annual precipitation is 552.7 mm, and the annual frost free period is about 172 d.

1.2 Data materials The meteorological and freezing damage data from individual cases of freezing damage during *F. suspensa* flowering period in Anze County from 2018 to 2025 was used. Meteorological data: daily average temperature, daily minimum temperature, sunshine hours, *etc.* of various meteorological automatic observation stations in Anze County during the freezing damage period of *F. suspensa* during March – April from 2018 to 2025. Freezing damage data: through literature search, investigation, and other methods, multiple sources were collected to record the freezing damage during the flowering period of *F. suspensa* in Anze County from 2018 to 2025. The content of the freezing damage records included the freezing time, location (township, village), altitude, freezing rate, yield reduction rate, and other information.

1.3 Design and analysis methods The design of meteorological index insurance products generally includes: investigation and analysis, data collection and organization; selection of key influencing factors and determination of threshold values; construction of the relationship model between meteorological index and yield reduction rate; determination of pure insurance premium rate; improvement of product design. The selection of meteorological indices, the construction of the relationship model between meteorological indices and loss rates, and the determination of pure premium rates are key factors affecting the design of meteorological index insurance. Therefore, using the example of *F. suspensa* freezing damage and consulting relevant information, the critical temperature of freezing damage was determined. Based on the critical temperature and duration of freezing damage, the freezing damage index was calculated. Based on the freezing damage index and yield reduction rate, a disaster damage assessment model was established. Using the expected historical payout ratio as the pure insurance premium rate, design of other parameters such as insurance liability, insurance period, and payout standards was completed at the same time.

2 Results and analysis

2.1 Critical temperature for freezing damage during the flowering period of *F. suspensa* Research has shown that the lowest temperature is the most important factor in freezing damage indicators, while the duration of low-temperature weather is the cause of freezing damage and an important factor in determining the degree of freezing damage. When the lowest temperature is below a certain value, freezing damage is highly likely to occur, therefore it is the critical temperature for freezing damage. Research and disaster investigations have shown that the loss of yield caused by freezing during the flowering period of *F. suspensa* is not only related to a single strong low-temperature freezing process, but also to the cumulative damage caused by multiple consecutive low-temperature freezing processes. Therefore, when selecting the freezing damage index during the flowering period of *F. suspensa*, the meteorological index should reflect the degree of yield loss as much as possible. From April 21 to 25, 2020 in Anze, there was a occurrence of continuous low temperature hazards for 4 d during the flowering period of *F. suspensa*. The lowest temperature in Liangma Township was −9.2 ℃, and all *F. suspensa* were frozen to death. Therefore, the duration of freezing damage, extreme low temperature, and thawing temperature difference were selected as meteorological indices for freezing damage during the flowering period of *F. suspensa*.

Using the lowest temperature data of freezing damage events during the study period, combined with the results of the *Study on Freezing Damage Indicators during the Flowering Period of Forsythia suspensa in Anze County*[10], the critical value of the lowest temperature for freezing damage index during *F. suspensa* flowering period was determined (Table 1).

Table 1 Critical temperature for freezing damage during the flowering period of *F. suspensa*

Freezing damage level	Minimum temperature//℃	Duration//h	Symptoms of flowers after freezing	Loss rate//%
Mild	≤ −2.0	≥2	Some petal edges may show slight wilting or discoloration, with little impact on overall flowering and pollination	≥30
Moderate	≤ −3.0	≥3	Most flowers are frozen, with large areas of petals turning brown, wilting and drooping, and freezing damage to the stigma and anthers	≥70
Severe	≤ −4.0	≥2	The entire corolla turns black and falls off, and the young shoots at the top of the new shoots die from freezing, resulting in a basic loss of yield in that year	≥90

2.2 Freezing damage index The flowering period of *F. suspensa* in Anze County is generally from March 20 to May 30. According to the freezing damage data collected from the disaster reporting system of the China Meteorological Administration, there

were three severe freezing damage events during the flowering period of *F. suspensa* in Anze County from 2018 to April 2025. With global climate change, spring temperatures are increasing year by year, and the flowering period of *F. suspensa* is advancing. Phenological observation data of *F. suspensa* confirms this viewpoint. In 2023, *F. suspensa* in Liangma Township, Anze County entered the budding stage on March 16, the flowering stage on March 24, the universal flowering stage on March 30, and the fruiting stage on April 18[10]. Therefore, the insurance period for *F. suspensa* freezing damage was set as March 20 to April 30 ($n=42$), and the daily minimum temperature during the research period was analyzed. Using the formula for freezing damage index F (freezing damage process) and the critical temperature T_{cp} for freezing damage calculated earlier, the calculation is as below[11]:

$$F=\sum_{i=1}^{n} f(D_i) \quad f(D_i)=\begin{cases}1 & (T_i \leqslant T_{cp}) \\ 0 & (T_i > T_{cp})\end{cases} \tag{1}$$

n is the natural days during the insurance period; D_i is the daily sequence during the insurance period; $f(D_i)$ is the judge function and returns 0 or 1. T_i is the daily minimum temperature; T_{cp} is the critical temperature for freezing damage. According to the calculation results in the previous text, $T_{cp}=-2.0$ ℃. If $T_i \leqslant T_{cp}$, that is, the temperature is below the critical temperature for freezing damage, the freezing damage days will increase by 1 d. On the contrary, if $T_i > T_{cp}$, that is, the minimum temperature does not reach the critical temperature for freezing damage, there will be no freezing damage, and the freezing damage days will not increase.

The days with temperature $T \leqslant -2.0$ ℃ occurring from March 20 to April 30 each year from 2018 to 2025 was calculated. The freezing damage index obtained from the formula (1) was 33 d.

$$\text{Mean freezing damage index: } \overline{F}=\frac{1}{k}\sum_{j=1}^{k} F_j \tag{2}$$

where k is the number of years in which freezing damage occurred; F_j is the freezing damage index for the j^{th} year of freezing damage. According to Table 1 and formula (2), it is obtained: $\overline{F}=4.125$.

2.3 Establishment of a disaster loss assessment model for freezing damage Based on meteorological data during the flowering period of *F. suspensa* from March 20 to April 30, 2018 – 2025, yield damage, literature review, and online information on the freezing damage process, the Pearson correlation coefficient method was used to comprehensively analyze the results. The correlation between the freezing damage index and the extremely minimum temperature, the duration of freezing damage, and the thawing temperature difference during the freezing damage process was found to be significant, making it the main factor causing freezing damage during the flowering period of *F. suspensa*. A freezing damage assessment model was built based on this (Fig. 1): $y=50.403\ln(x)+31.085$, where y is yield reduction rate; x is freezing damage index. The coefficient of determination $R^2=0.735\,2$, indicating that 73.52% of the change in yield reduction rate can be explained by the natural logarithm of the freezing damage index, and the model fitting effect is good.

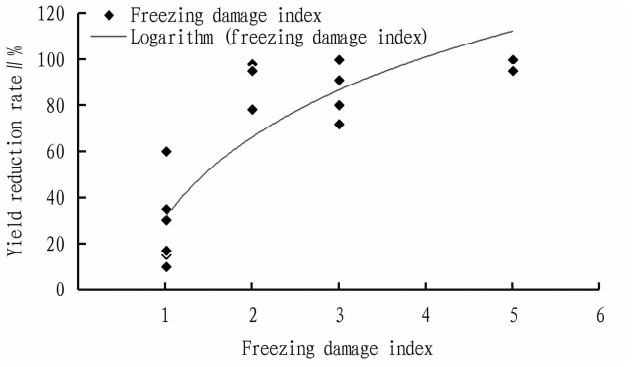

Fig. 1 Scatter plot and simulation curve of freezing damage index and yield reduction rate

2.4 Determination of pure insurance premium rate The core of insurance pricing is the determination of pure insurance premium rate. The pure insurance premium rate is equal to the expected value of the insured's loss, which can be calculated using the average historical loss rate of crops[12]:

$$R=\frac{E(L)}{\lambda\mu} \tag{3}$$

where R is pure insurance premium rate; λ is insurance ratio; μ is expected relative yield per unit area; L is loss ratio; $E(L)$ is expected loss of the target crop, *F. suspensa*. For the *F. suspensa* meteorological index insurance, λ and μ in the Anzhe area are generally taken as 100%, and the pure premium rate of *F. suspensa* meteorological index insurance can be written as[12]:

$$R=E(L)=\sum_{i=1}^{m} x_i p_i \tag{4}$$

where x_i shows yield reduction rate at the i^{th} level; p_i shows occurrence probability of yield reduction rate at the i^{th} level; m shows level of yield reduction rate. Considering the small sample size of *F. suspensa* yield data, this paper adopted the consistency of *F. suspensa* yield risk, that is, insurance premium $P=RQ$, where Q is the unit area insurance amount of *F. suspensa* freezing damage index insurance during flowering period. Freezing damage insurance for Chinese herbal medicine falls within the scope of policy insurance, therefore no deductible conditions are set. According to the actual compensation trigger condition of the freezing damage index insurance during the flowering period of *F. suspensa* in Anze County, when the freezing damage index is set to 1 d, the claim will be initiated. Due to the fact that the flowering and fruiting period of *F. suspensa* in Anze County is generally from late March to the end of April, the freezing damage insurance period is from March 20 to April 30. The freezing damage level is shown as Table 2.

Table 2 Frost damage level of *F. suspensa*

Level	Yield reduction rate L // %	Probability of occurrence P // %
Mild	$10 \leqslant L < 30$	18.7
Moderate	$30 \leqslant L < 70$	25.0
Severe	$70 \leqslant L < 90$	18.7
Super severe	$L \geqslant 90$	37.5

According to Table 2 and formula (4), the pure premium rate $R = 0.55$. So the insurance premium for freezing damage during the flowering period of *F. suspensa* in Anze County was calculated based on $P = 0.55Q$, where Q is the unit area insurance amount for the freezing damage index insurance during the flowering period of *F. suspensa*.

3 Discussion

Previous studies have shown that the degree of freezing damage during the flowering period of *F. suspensa* is not only related to the intensity and duration of cold air, but also to the specific timing of its flowering. According to meteorological data and the experience of growers, the flowering and fruiting period of *F. suspensa* varies from year to year. From March to April of 2018 – 2025, there were a total of 16 freezing damage events of varying degrees. In the past 10 years, Anze County has not experienced low temperature weather below −2.0 ℃ in early May. For the convenience of insurance claims, the latest flowering period and young fruit period in May can be ignored, and the freezing damage meteorological index can be simplified to ensure that the insurance coverage period can cover the entire flowering period. However, this paper did not delve into the contribution of terrain to the reduction of *F. suspensa* yield. Therefore, further testing and correction will be conducted in practice to improve the design of frost damage index during the flowering period of *F. suspensa*.

4 Conclusions

(1) The average freezing damage index during the flowering period of *F. suspensa* in Anze County was 4.1 d, and the frequency of freezing damage occurrence was 9.8%.

(2) The freezing damage index during the flowering period of *F. suspensa* was positively correlated with the duration of freezing damage and thawing temperature difference, with correlation coefficients of 0.893 117 and 0.644 99, respectively. It was negatively correlated with the extremely minimum temperature, with a correlation coefficient of −0.767 81.

(3) The correlation between the meteorological index F of freezing damage during the flowering period of *F. suspensa* and the yield reduction rate was significant, and there was a positive nonlinear relationship between F and the yield reduction rate.

(4) The flowering period and young fruit period of *F. suspensa* in Anze County are generally from late March to early May. To ensure that the insurance coverage period can cover the entire flowering period, the coverage period was set from March 20 to April 30. When the trigger condition for compensation was $F = 1$ d, the compensation process was initiated. The insurance premium for freezing damage was calculated based on $P = 0.55Q$, where Q is the unit area insurance amount for the freezing damage index insurance during the flowering period of *F. suspensa*.

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