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GIS-Based Risk Assessment of Hail Disasters Affecting Cotton and Its Spatiotemporal Evolution in China

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Abstract: Understanding the spatiotemporal distribution pattern of hail disaster risk for cotton is crucial in mitigating hail disaster and promoting the sustainability of cotton farming. Based on such indexes as hail disaster frequency, spatiotemporal exposure, and vulnerability of cotton, we assess hail disaster risk for cotton, and analyze its spatiotemporal pattern and evolution in Mainland China from 1950 to 2009, supported by geographic information system (GIS). The following conclusions are drawn: (1) The proposed risk assessment method reveals the spatiotemporal difference of hail disaster risk for cotton at the county level. (2) Hail disaster risk for cotton is low in China, except for north of the North China Plain and the cotton-planting areas in Xinjiang Uygur Autonomous Region. From 1950 to 2009, hail disaster risk for cotton gradually increased. (3) The descending orders of hail disaster risk levels for cotton are bud stage, seedling stage, sowing and seeding stage, boll stage, and boll opening stage. The growth period with the highest risk varies across the cotton-planting areas. (4) The results of this paper are important for developing hail disaster prevention and reduction measures.

Keywords: hail disasters; cotton; risk assessment; spatial distribution; growth periods; dynamic variation; GIS

1. Introduction

Hail is an abrupt weather phenomenon [1]. Although the effects of hailfalls usually interest limited areas, the damages can be severe [2], especially to agriculture [3–8]. Therefore, assessing the risk of hail disaster is crucial in promoting sustainable agriculture [9]. Further, spatiotemporal analysis of hail disaster risk, including the distribution, intensity, frequency and reference period, will provide important information for decision-makers in developing corresponding mitigation planning and management countermeasures [10,11]. However, more efforts are still needed to summarize and reveal the spatiotemporal characteristics of hail disaster risk, beyond numerous case studies.

Most previous studies failed to reveal the spatiotemporal characteristics of hail disaster risk because of the conceptual confusion of hail event and hail disaster. It is well known that hail events do not necessarily lead to hail disasters, and only those that have caused losses to hail-affected bodies can be identified as hail disasters. According to statistics, only 5% to 10% of hailfalls may cause severe losses [3]. Unfortunately, many scholars studied the spatiotemporal pattern of hails employing datasets of hailfall events instead of hail disasters. For example, Baldi *et al.* [2] studied the frequency and geographical distribution of hails over Italy using datasets from meteorological stations, hailstorm reports, and NCEP/NCAR daily reanalysis; Giaiotti *et al.* [12] studied the spatiotemporal pattern of hails over Friuli Venezia Giulia of Italy using hailpad data; Leslie *et al.* [13] estimated the future trends in severe hailstorms over the Sydney Basin, using coupled climate model simulations under both fixed (no change) greenhouse gas concentrations and the IPCC SRES A1B future climate scenario; Počakal *et al.* [14] analyzed the spatiotemporal distribution of hails over the continental part of Croatia using the data recorded at hail suppression stations; and Mezher *et al.* [15] studied the time periods and geographical distribution of hails over Argentina from 1960–2008 using the data from weather stations. Many Chinese scholars have also developed a series of spatiotemporal studies of hail on the national [16–18], inter-provincial [19], provincial (such as Beijing [20], Jiangsu [21], Fujian [22], Ningxia [23], Jilin [24], Yunnan [25] and Guizhou [26]) and county scales [27–30]. The datasets used in the above studies mainly include two kinds, one is hail event records from meteorological stations, hail suppression stations, hailpad or radiosonde, and the other is hail event predictions using NCEP/NCAR reanalysis or IPCC future climate scenarios. However, the main information of these datasets is the frequency of hailfalls. The information about losses caused by hailfalls to the affected bodies is seldom included. Therefore, although previous studies are helpful in recognizing spatial distribution, regional variation, time cycles such as annual, seasonal and monthly of hails, they can neither reflect the space and time patterns of hail disasters, nor, of course, reveal the spatiotemporal characteristics of hail disaster risks.

Although some scholars further explored the spatiotemporal characteristics of hail disasters, there are few studies concerned with specific hail-affected bodies. For example, Vinet analyzed the distribution of hail disasters in France [31]. Changnon analyzed the spatiotemporal distribution of hail disaster property loss from 1949 to 2006 in the United States [32]. Webb *et al.* analyzed the spatiotemporal distribution of hail disasters in Britain and assessed the hail hazards in the UK and Ireland [33]. Sioutas *et al.* studied the frequency, distribution and intensity of hail disasters over northern Greece based on the data from meteorological stations, insurance and hail suppression stations [34]. Using the data obtained from meteorological stations, *Encyclopedia of Meteorological Disasters in China*, *Disaster Reduction in China* and general survey of disasters, Chinese scholars studied the spatiotemporal distribution of hail disasters over China [9,35] as well as on a provincial scale, including Xinjiang [36–39], Liaoning [40], Heilongjiang [41], Chongqing [42] and Tibet [43]. However, the results of these studies can only reflect the regional differentiation of hail disasters, and cannot reveal the differences between specific hail-affected bodies, because these studies take a region itself as the research object, without distinguishing different hail-affected bodies inside the region. It is well known that, even under the same intensity of hail strike, the vulnerability and exposure differences of hail-affected bodies lead to different loss intensities [44]. In conclusion, there are few studies on the spatiotemporal pattern of hail disaster risks relating to specific hail-affected bodies. Therefore, it is urgent to conduct relevant studies to provide a scientific basis for developing elaborate hail disaster risk mitigation strategies, according to the spatiotemporal pattern of hail disaster risk subjects to specific hail-affected bodies.

China is one of the countries subject to the most severe hail disasters [7], and is also the largest cotton-producing country in the world [45]. Unfortunately, hail disasters occur frequently in most of China's major cotton-producing areas [46]. Cotton is very sensitive to hail strike [47]. In China, what makes it even worse is that the hail occurrence periods almost coincide with the growth periods of cotton, thus causing very severe losses [9,16–18,46]. Therefore, the main goal of this study is to propose an analytical procedure that helps assess the risk of hail affecting cotton, using the hail disaster data in the GIS environment. In the following sections, we will first describe the methodological framework.

Then, the proposed method will be applied to assess the hail disaster risk for cotton regarding the spatiotemporal pattern and evaluation. Lastly, we discuss how the research findings can be used broadly to mitigate hail disaster risk for cotton.

2. Methodology

2.1. Data Sources

The primary data employed is the database recorded with a total of 27,076 hail disaster cases in mainland China from 1950 to 2009 [9], the data sources of which are shown in Table 1.

Table 1. Data sources of hail disaster cases.

Data name	Contents	Source
Encyclopedia of Meteorological Disasters in China [48]	Data on hail disaster cases in the counties all over China from 1950 to 2000	China Meteorological Press
China Meteorological Disasters Yearbook [49–53]	Data on hail disaster cases in the counties all over China from 2005 to 2009	China Meteorological Press
Disaster Reduction in China [54–57]	Data on hail disaster cases in the counties all over China from 2001 to 2004	National Disaster Reduction Center of the Ministry of Civil Affairs of China
Newspaper-based Disaster Database of China	Data on hail disaster cases in the counties all over China from 1950 to 2005	Newspapers
Web Retrieved Data	Data on hail disaster cases in the counties all over China from 2008 to 2009	Internet media

The hail disaster cases mainly come from the publications of *Encyclopedia of Meteorological Disasters in China* [48], *China Meteorological Disasters Yearbook* [49–53] and *Disaster Reduction in China* [54–57]. Both of the publications record hail disaster cases daily at the county level from 1950 to 2009, and only the hail events causing loss were included in the database. Unfortunately, widely accepted criteria about losses has not been established to determine whether a hail event could be regarded and recorded as hail disaster. However, there are still some studies proposing the criteria to determine hail disasters. For example, the *Encyclopedia of Meteorological Disasters in China* [48] defines a hail disaster only as a hail occurrence area that affects more than two counties. *China Meteorological Disasters Yearbook* [49–53] defines it as hail events that affect more than 1000 hm^2 agricultural areas, that cause the death of two or more people, or that cause direct economic losses of more than RMB 10 million. Although the threshold between hail events and hail disasters of the other data sources, such as *Disaster Reduction in China* [54–57], Newspaper-based Disaster Database of China and Web Retrieved Data, is not uniform, whether the hail event induced damages and yield losses to hail-affected bodies is the only threshold to distinguish hail events and hail disasters. These datasets are the most comprehensive hail disaster records in China, although some hail disasters in outlying areas may be missed. However, these missing cases have little impact on the overall research results. Therefore, these datasets have been widely used in hail disaster research [9,33–41].

The hail disaster cases beyond the growth periods of cotton are insignificant for the analysis of hail disaster risk for cotton. In the hail disaster case database, since every case contains the records of county name and occurrence date, the required data can be screened out according to the time span of cotton growth periods. Therefore, five sub-databases were extracted from the Chinese hail disaster case database by selecting records from the case database according to the growth periods of the four cotton-planting areas: database of hail disaster cases at sowing and seeding stage of cotton in China (2415 cases), database of hail disaster cases at seedling stage of cotton in China (7864 cases), database of hail disaster cases at bud stage of cotton in China (5823 cases), database of hail disaster cases at boll stage of cotton in China (8093 cases), database of hail disaster cases at boll opening stage of cotton in China (2405 cases) (Figure 1, Table 2).

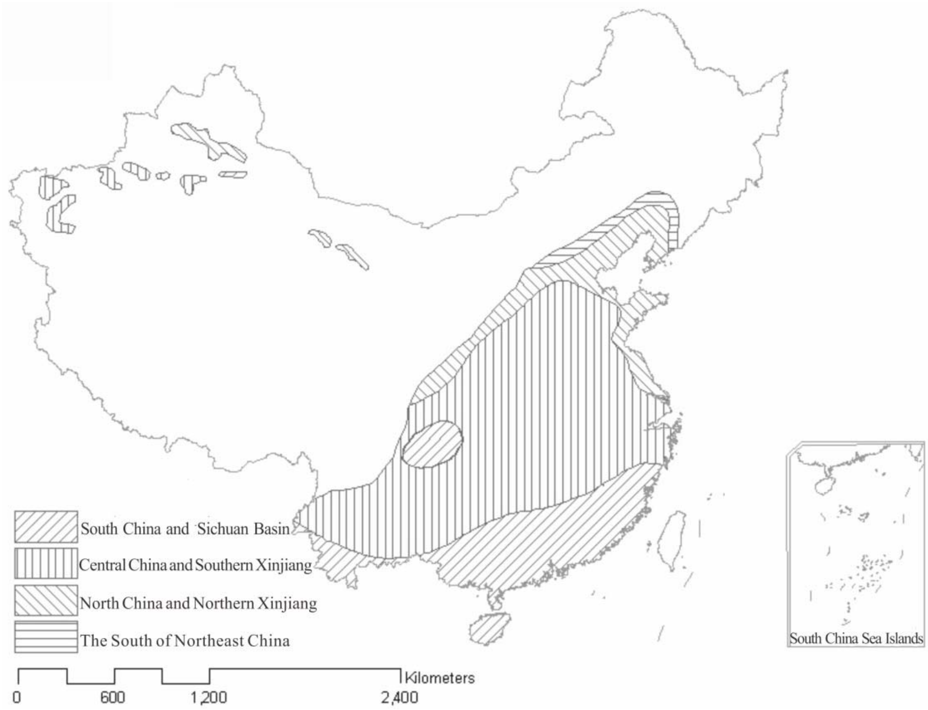


Figure 1. Zone map of the growth periods of cotton-planting areas in China (data sources [58]).

Table 2. Schedule of the growth periods of cotton in China (month/day) [1].

Cotton planting area	Sowing and seeding stage (s1)	Seedling stage (s2)	Bud stage (s3)	Boll stage (s4)	Boll opening stage (s5)
Southern China and Sichuan Basin	1–20 April	21 April –10 June	11 June–5 July	6 July–25 August	26 August–15 October
Central China and Southern Xinjiang	5–25 April	26 April–15 June	16 June–10 July	11 July–30 August	1 September–20 October
Northern China and northern Xinjiang	10–30 April	1 May–20 June	21 June–15 July	16 July–5 September	6 September–1 November
Northeastern China	15 April–5 May	6 May–25 June	26 June–20 July	26 July–5 September	6 September–1 November
Duration (days)	20	50	25	50	50

[1] Data sources [59].

The other datasets used include China's land use data in 2005 and China's cotton yield at the county level in 2008 provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC-CAS) [60]. The administrative divisions spatial database of China (in 2000, 1:4 million) was provided by National Geomatics Center of China.

2.2. Method for Assessing Risk of Hail Disaster Affecting Cotton

2.2.1. Theoretical Framework

The most widely recognized disaster risk definition [61] was put forward by the International Strategy for Disaster Reduction of United Nations (UNISDR) [62] and Dilley *et al.* [63]. UNISDR defined risk as a function of hazard and vulnerability [62], while Dilley *et al.* [63] suggested that the disaster risk should be mainly determined by the following three factors: hazard, vulnerability and exposure.

We argue that exposure is an important property of crops, compared with other hail-affected bodies, such as cars and buildings. For cotton, its exposure covers the spatial distribution of planting and temporal distribution of growth. Only the hail disaster cases within planting areas and during the growth periods of cotton are of significance to assessing hail disaster risks. Otherwise, the assessment results will not be able to reveal the spatiotemporal characteristics of hail disaster risk for cotton.

Hence, the hail disaster risk for cotton (R) is a function of the hail hazard (H), spatial exposure (E_s), temporal exposure (E_t) and vulnerability (V) of cotton, as Equation (1):

$$R = f(H, E_s, E_t, V) \tag{1}$$

2.2.2. Hail Hazard Index (H)

There are generally two methods for assessment on hail hazard (H). One is to assess H according to hail diameters, hailfall duration and, accordingly, wind speed [33,34,39,43,64,65]. But the above hail parameters are very difficult to get. The other method calculates H using the frequency of hail days [66–68]. In some studies, the total hail days [10], average annual hail days [67] or hail days within a specific period [69] were directly applied as the index for assessment on H. Some studies further constructed the standardized index [70,71] and hail frequency index [72,73] to assess H based on hail days. In this paper, the historical frequency of hail disasters affecting cotton was taken as the index, and a standardized hail hazard intensity index over a county was calculated using the following Equation (2):

$$H_i = \frac{f_i - f_{t\min}}{f_{t\max} - f_{t\min}} (i = 1, 2, ..n) \tag{2}$$

where H_i is the hail hazard index over county i, f_i is the total frequency of hail disasters affecting cotton over county i, f_{tmin} is the minimum total frequency of hail disasters affecting cotton over all counties, and f_{tmax} is the maximum total frequency of hail disasters affecting cotton over all counties. The data on the frequency of hail disasters affecting cotton is screened out by extracting hail disaster case data sets [9] according to the time span of the growth periods of cotton (Figure 1 and Table 2).

To further reveal the variation laws of hail hazard of cotton in different areas with the growth periods, the calculation formula for hazard index of hail disasters affecting cotton in a growth period over a county is as follows:

$$H_{ij} = \frac{f_{ij} - f_{\min}}{f_{\max} - f_{\min}} \ (i = 1, 2, ..\mathrm{n}, j = \mathrm{s}1, \mathrm{s}2, \mathrm{s}3, \mathrm{s}4, \mathrm{s}5) \tag{3}$$

therefore,

$$f_{\min} = \min\left\{f_{ij}\,|i = 1, 2, ...n,\ j = s1, s2, s3, s4, s5\right\} \tag{4}$$

$$f_{\max} = \max\left\{f_{ij}\,|i = 1, 2, ...n,\ j = s1, s2, s3, s4, s5\right\}\ , \tag{5}$$

where H_{ij} is the hail hazard index of cotton in the growth period j over county i, f_{ij} is the total frequency of hail disasters affecting cotton in the growth period j over county i, f_{min} is the minimum total frequency of hail disasters affecting cotton in all growth periods over all counties, and f_{max} is the maximum total frequency of hail disasters affecting cotton in all growth periods over all counties. The frequency of hail disasters affecting cotton at sowing and seeding stage, seedling stage, bud stage, boll stage and boll opening stage in a county comes from the corresponding database of hail disasters from 1950 to 2009 over mainland China.

2.2.3. Exposure (E) and Vulnerability (V) of Cotton

Exposure (E) refers to cotton being exposed to the effects of hail. Specifically, it refers to cotton's physical exposure, including spatial distribution (E_s) regarding its planting areas, and temporal exposure (E_t) regarding its growth stages. We assume that the cotton-planting areas are dry farmlands in a cotton-planting county. Additionally, a cotton-planting county is defined as a county that has statistically cotton yields. Thus, the cotton-planting areas can be obtained by spatial analysis using GIS with support of datasets of land use, cotton output by county and administrative division of China.

Where there is cotton planted, E_s is assigned as 1, or 0 where there is no cotton planted. E_t has been reflected in the screening for cases of hail disasters affecting cotton (see paragraph 3 of Section 2.1).

Vulnerability (V), one of the core variables of risks, generally refers to the degree of harm, loss and disruption of an entity triggered by a natural hazard [44]. V is usually calculated using data of loss. However, because of data limitation, V is expressed as the area ratio of cotton-planting areas in a county, and the greater the value is, the higher the county's possibility to loss of cotton yield subject to hail hazard will be, and vice versa.

2.2.4. Calculation of Hail Disaster Risk for Cotton

Based on the conceptual model (Equation (1)) and above analysis, the hail disaster risk for cotton over a county is calculated as per Equation (6):

$$R_i = H_i \times V_i \tag{6}$$

where R_i is the hail disaster risk for cotton over county i, H_i is the hail hazard index over county i, and V_i is the vulnerability of cotton over county i.

The calculation formula for risk index of hail disasters affecting cotton in a growth period over a county is:

$$R_{ij} = H_{ij} \times V_i \tag{7}$$

where R_{ij} is the hail disaster risk for cotton over county i in the growth period j, H_{ij} is the hail hazard index over county i in the growth period j, and V_i is the vulnerability of cotton over county i.

2.2.5. Ranking and Mapping of Hail Disaster Risk for Cotton

There are two kinds of risk levels, absolute level and relative level. For revealing the regional differentiation of hazard risk, relative risk is widely used because the data, which is limited by availability and quality, is inadequate for understanding the absolute level of risk [74]. However, even limited data is adequate for identifying the areas that are at relatively higher single—or multiple-hazard risk [63]. Therefore, relative risk was adopted in this paper, and the ranking of counties by relative risk level of hail disasters affecting cotton would provide a measurement for prioritizing risk management strategies.

The natural breaks method (Jenks) was applied to classify R_i and R_{ij} into five relative risk levels: extremely slight hail disaster, slight hail disaster, moderate hail disaster, severe hail disaster and extremely severe hail disaster. The idea of the natural breaks method consists of minimization of variance for objects from the chosen subsets and maximization of variance between the subsets [75]. The division of hail disaster risk for cotton into subsets provides the possibility for obtaining relatively homogeneous classes in terms of the level of hail disaster risk for cotton.

Further, thematic mapping and statistical analysis are conducted according to R_i and R_{ij} from the two perspectives of space unit (county scale) and time unit (growth periods of cotton), so as to reveal the pattern and evolution of hail disaster risk for cotton in different time-space domains and explore the difference between hail disaster risks for cotton between different growth periods.

2.3. Spatiotemporal Analysis Method

We applied Mann-Kendall method and spatial variance coefficient to analyze the spatiotemporal pattern of hail disaster risk for cotton.

Mann-Kendall (M-K) is a method to test abrupt climate change [76]. In M-K testing, the null hypothesis H_0 is the time series $(x_1, x_2, ..., x_n)$, which consists of n samples of independent and identically distributed random variables: The alternative hypothesis H_1 is subject to two-sided testing.

For all $i, j \leqslant$ n, and $i \neq j$, the distribution of x_i and x_j is different. The test statistic S is defined as per Equation (8):

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} sign(X_i - X_j) \tag{8}$$

where $sign()$ is the signum, and when $X_i - X_j$ is less than, equal to or greater than zero, $sign(X_i - X_j)$ is -1, 0 and 1 respectively. S is the normal distribution, of which the average is 0, and variance $Var(S) = n(n-1)(2n+5)/18$.

The M-K statistic formula when S is less than, equal to and greater than zero are respectively [77]:

$$\begin{cases} Z = (S-1)/\sqrt{n(n-1)(2n+5)/18}(S>0) \\ Z = 0(S=0) \\ Z = (S-1)/\sqrt{n(n-1)(2n+5)/18}(S<0) \end{cases} \tag{9}$$

Coefficient of variance, also called "standard deviation coefficient", is another statistic index to measure the degree of variation in observations in the data, which can eliminate the effect of the difference in unit or average on degree of variation of the data from two or more stations, and it is also a commonly used parameter in the spatial analysis [78].

To reveal the degree of variation of hail disasters over the cotton-planting counties in multiple years, the coefficient of variance of a county is calculated according to the Equation (10) :

$$Cv_i = \sqrt{\frac{1}{N} \sum_{i=1}^{i=N} (x_i - u_i)_2} \tag{10}$$

where Cv_i is the coefficient of variance of county i in 60 years, u_i is the average annual frequency of hail disaster over the county i, x_i is the annual frequency of hail disaster over the county i, and N is the 60 years from 1950 to 2009.

2.4. Technological Flow and Application of GIS

The technological flow is shown in Figure 2. GIS has been widely used in disaster research [69,72,73,79]. In this research, the whole process of risk assessment of hail disasters affecting cotton, including data management, index construction, model running, thematic mapping, spatial and statistical analysis, were carried out with support of GIS platform.

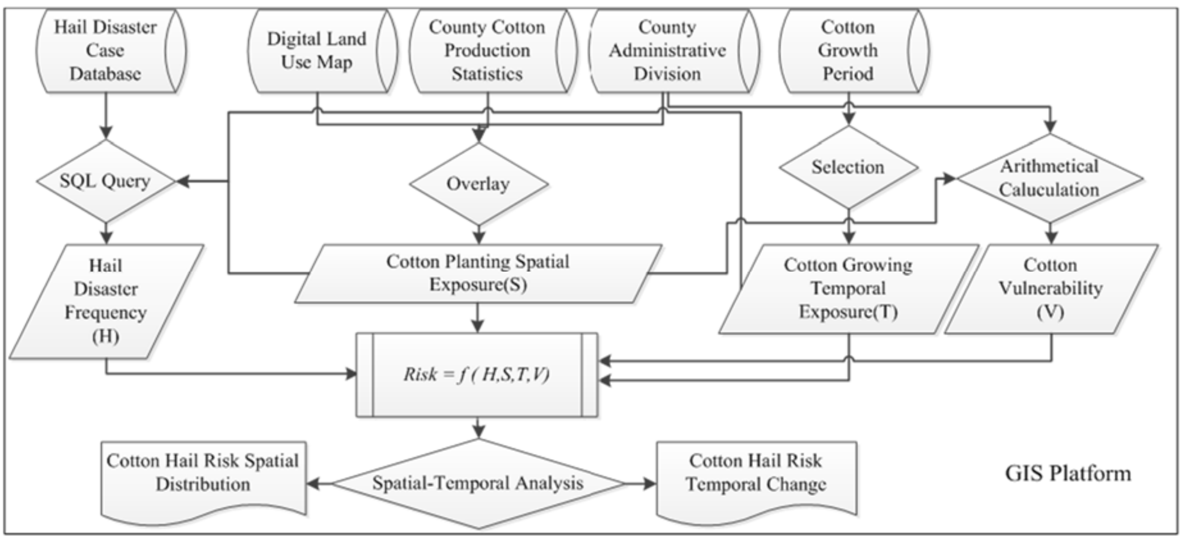


Figure 2. GIS based risk assessment of hail disasters affecting cotton and its spatiotemporal analysis.

3. Results

3.1. Spatial Distribution of Hail Disaster Risk for Cotton in China

The cotton-planting counties are widely distributed in China, and their climate varies greatly, with the average annual precipitation ranging from 100 mm to 2000 mm. Statistically, there were 921 cotton-producing counties in China in 2008 [52,60]. Due to the changes in administrative division, 849 counties were selected in the end, accounting for 92.18% of the cotton-planting counties in 2008. Based on this, the spatiotemporal pattern of hail disaster risks for cotton in China was analyzed.

3.1.1. Regional Distribution Characteristics

The distribution of hail disaster risk for cotton over counties in China is shown in Figure 3 (figure in brackets is county number). As to hail disaster risks, 481 counties are subject to extremely slight hail disaster, accounting for 56.65% of all the cotton-planting counties; counties subject to slight, moderate, severe and extremely severe hail disasters account for 29.68%; 10.61%, 2.59%, 0.47%, respectively. On the whole, the hail disaster risk level of cotton in China is low, while the counties with hail disaster risk above moderate level account for 13.67%.

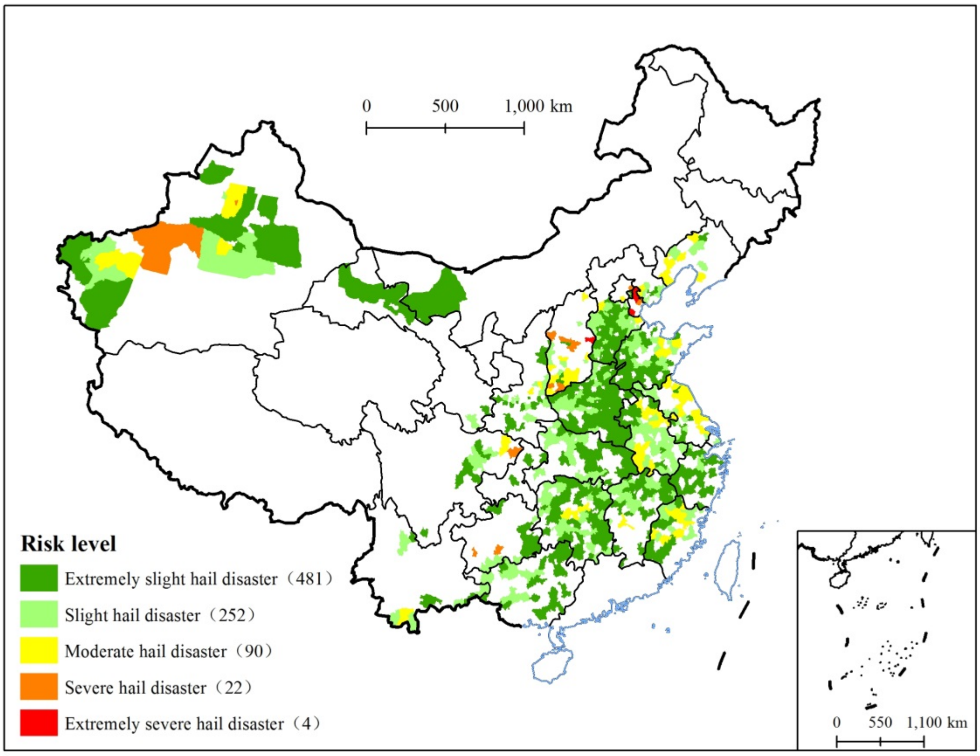


Figure 3. Hail disaster risk for cotton over counties in China (from 1950 to 2009).

The spatial pattern of hail disasters affecting cotton is quite different from those of previous studies on hail event and hail disaster. Zhang and Gao [16] and Zhang *et al.* [17] find that hail occurs most frequently in the high mountainous areas and northern plains. As a result, the highest hail frequency occurs over the central Tibetan Plateau. Zhao *et al.* [9] point out that there are eight hail disaster centers in China, include the Loess Plateau, Bohai Rim, Northeast Plain, Yunnan-Guizhou Plateau, Jianghuai Plain, Aksu Prefecture in Xinjiang, Eastern Qinghai and Central China. Our results show that the counties with hail disaster risk above moderate level are mainly distributed in the North China Plain, Central China, Xinjiang Uygur Autonomous Region, Sichuan Basin. The counties especially subject to extremely high hail disaster risk are all in the north of the North China Plain, respectively Jinghai County, Baodi County and Ji County of Tianjin City and Xiyang County of Shanxi

Province. North China Plain is a traditional cotton-planting area, and Xinjiang Uygur Autonomous Region is developing into one of China's largest cotton-growing areas, so the cotton within these areas still face great threat of hail disasters, and more attention should be paid to it.

Our study also suggest that the information of spatial distribution of hail events and hail disasters is insufficient for preventing hail disasters of a specific hail-affected body. This proves that it is crucial to study spatiotemporal pattern of hail disaster risk subjects to specific hail-affected bodies.

3.1.2. Spatial Variance Characteristics

The distribution of spatial variance coefficient for hail disaster risk for cotton over counties in China is shown in Figure 4.

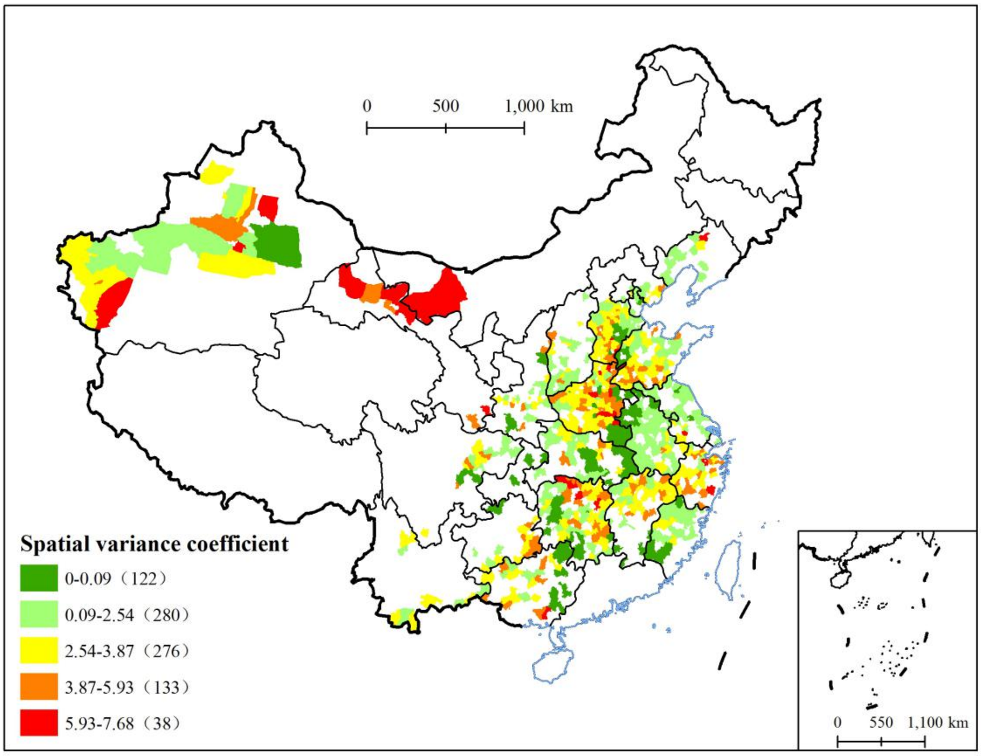


Figure 4. Distribution of spatial variance coefficient of the hail disaster risk for cotton over counties in China.

The higher the coefficient of the great interannual fluctuation is, the lower the stable hail disaster is. It shows that the counties with a higher coefficient of variance (above 2.54) are mostly distributed in the Hexi Corridor as well as the Tarim Basin and Junggar Basin in Xinjiang Uygur Autonomous Region, the North China Plain, and the middle reaches of the Yangtze River. This means these areas have great interannual fluctuation in hail disaster occurrences. Numerous studies show that complex landforms result in higher fluctuation of hail occurrence, for example, mountainous areas [1,2,9,10,13–31,33,36–46]. However, the factors that affect thespatial variance of hail disasters affecting cotton need further analysis.

3.1.3. Distribution Characteristics in Different Growth Periods

The distribution of the hail disaster risk for cotton in China in different growth periods is shown in Figure 5.

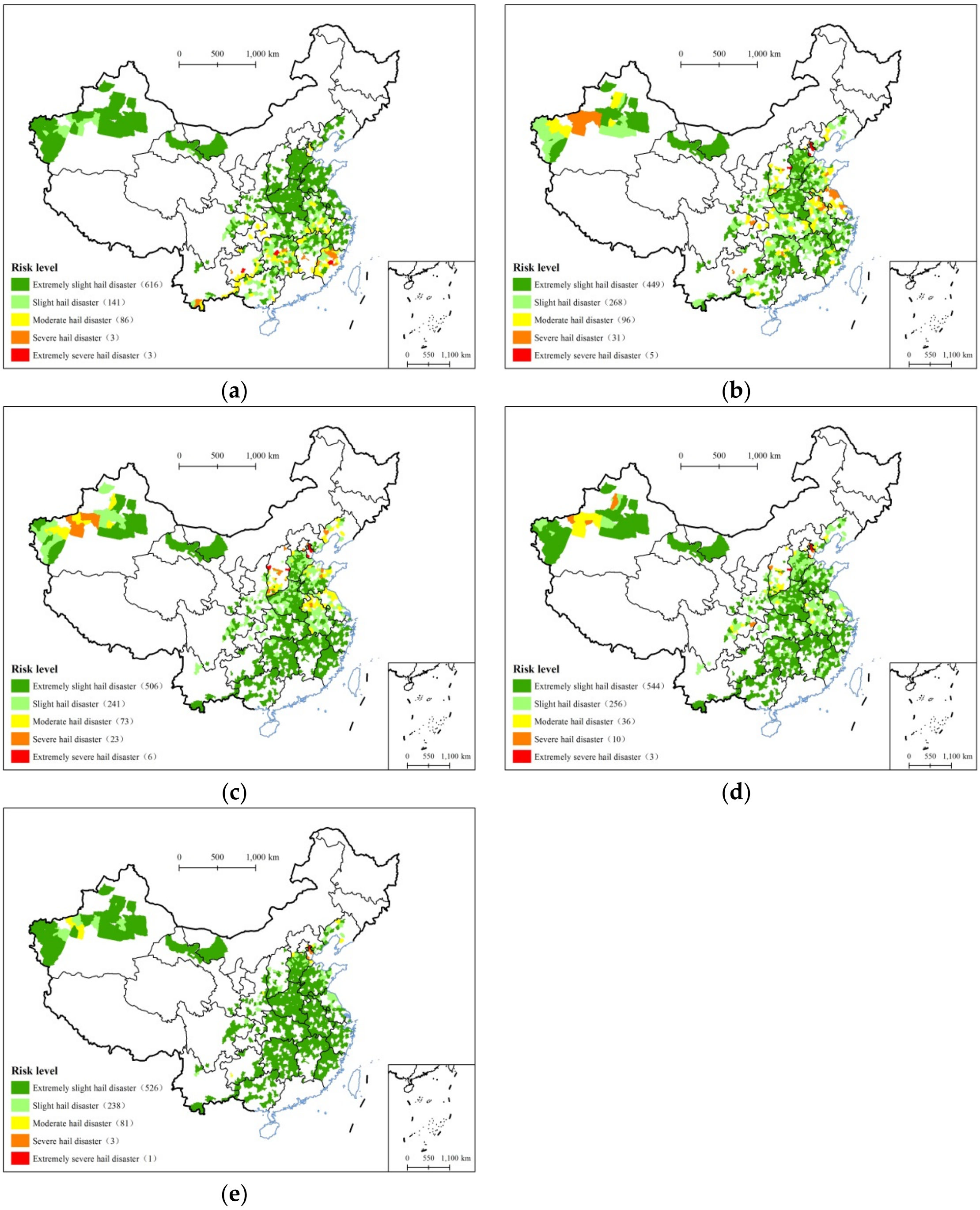


Figure 5. Hail disaster risk for cotton in China in different growth periods. (**a**) Sowing and seeding stage; (**b**) Seeding stage; (**c**) Bud stage; (**d**) Boll stage; (**e**) Boll opening stage.

At the sowing and seeding stage (Figure 5a), there are respectively 72.56%, 16.61%, 10.13% 0.35% and 0.35% counties with extremely slight, slight, moderate, severe and extremely severe hail disaster risk. Five of the top 10 counties with the highest risk are in Fujian Province, two in Hunan Province, two in Guizhou Province and one in Jiangxi Province. It shows that the hail disaster risk at sowing and seeding stage of cotton is low on the whole, and the relatively high risk areas are mainly in the above-mentioned areas in Southern China, where the cotton at sowing and seeding stage temporally and spatially coincides with the frequently occurred spring hail disasters in China [9].

At the seedling stage (Figure 5b), 52.89%, 31.56%, 11.31%, 3.65%, and 0.59% of counties are at extremely slight, slight, moderate, severe and extremely severe risk, respectively. The counties with moderate and even higher hail disaster risk are slightly more than those at the sowing and seeding stage. The counties with severe and extremely severe risk are mainly located in the east of the North China Plain (especially Tianjin City) and Xinjiang Uygur Autonomous Region because these areas are areas where hail disasters in late spring and early summer in China frequently occur [9].

At the bud stage (Figure 5c), 59.60%, 28.39%, 8.60%, 2.71% and 0.71% of counties are at extremely slight, slight , moderate , severe and extremely severe risk, respectively. This is higher than that at the sowing and seeding stage, but a little bit lower than that at the seedling stage. The counties with severe risk are mainly distributed in the north of the North China Plain and in the cotton-planting areas in Xinjiang Uygur Autonomous Region; three counties with extremely severe risk are located in Tianjin City, and another two are in Shanxi Province. The bud stage in the above-mentioned areas is from June to July, which coincides with the period in summer during which hail disasters frequently occur [9], thus leading to relatively high hail disaster risk.

At the boll stage (Figure 5d), 60.08%, 30.15%, 4.24%, 1.18% and 0.35% of counties are at extremely slight, slight , moderate, severe and extremely severe risk, respectively. Risk level is far less than that at the seedling and bud stages. The counties with severe hail disaster risk are mainly distributed in Xinjiang and north of the North China Plain, especially Tianjin City. This is because the cotton-planting areas in Northern China and Xinjiang Uygur Autonomous Region enter the bud stage from mid-July to early September, during which hail disasters in the above regions gradually decrease. After September, hail disasters rarely occur, so the hail disaster risk for cotton at the boll stage shows a declining trend.

At the boll opening stage (Figure 5e), 61.96%, 28.03%, 9.54%, 0.35% and 0.11% of counties are at extremely slight, slight, moderate, severe and extremely severe risk, respectively. The top 10 counties with the highest risk level are distributed in the North China Plain and Xinjiang Uygur Autonomous Region. The countries with severe and extremely severe risk level are all in Tianjin City.

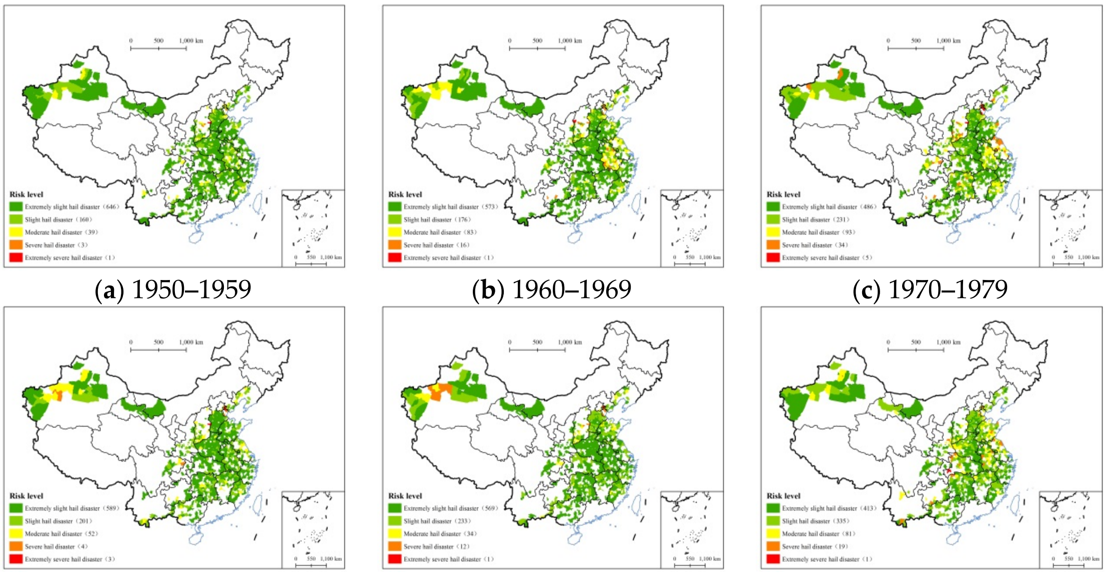
The study shows that, if the cotton suffers from hail disasters at the sowing and seeding stage, reseeding can be conducted, or it can be recovered to some extent [80], whereas, if the cotton suffers from hail disasters at the bud stage, it usually cannot be recovered, thus leading to a great loss in yield. Our studies indicate that, at the bud stage, cotton shows the highest vulnerability, and hail disasters have the greatest impact on its yield [81,82]. Therefore, statistically, the descending order of hail disaster risk levels for cotton is bud stage, seedling stage, sowing and seeding stage, boll stage, and boll opening stage. In terms of geographical distribution, hail disaster risk is relatively high in the cotton-planting areas in the north of the North China Plain and Xinjiang Uygur Autonomous Region.

3.2. Temporal Variation of the Hail Disaster Risk for Cotton in China

3.2.1. Interdecadal Variation

Hail disaster risk for cotton over counties in China in each decade is shown in Figures 6 and 7.

Figure 7 shows that the areas with severe and extremely severe hail disaster risk vary in different decades. From 1950 to 1959, only 4 counties suffered from severe and extremely severe hail disasters, mainly distributed in the north of the North China Plain, while, from 1960 to 1969, such counties increased to 17, distributed in the north of the North China Plain and the Huaihe River Plain. From 1970 to 1979, such counties substantially increased to 39, mainly distributed in the south of the Northeast China Plain, north of the North China Plain and south of the North China Plain and Sichuan Basin. Then, in 1980 to 1989, the number of such counties decreased to 7, mainly distributed near the north of the North China Plain and the Tianshan Mountains in Xinjiang Uygur Autonomous Region. From 1990 to 1999, there are 13 counties suffering from severe and extremely severe hail disasters, mainly distributed nearby the Tianshan Mountains in Xinjiang Uygur Autonomous Region and in the north of the North China Plain. Then, from 2000 to 2009, such counties increased to 20, mainly distributed in Middle-Lower Yangtze plains and most regions in the north of the North China Plain. Furthermore, the average hail disaster risk level over the cotton-planting counties in China in each decade is 0.0217, 0.0342, 0.0314, 0.0254, 0.0333, and 0.0350 (Figure 8). It shows a variation trend of increase-decrease-increase, and goes up with fluctuations. The two peaks appeared respectively in the 1960s and from 2000 to 2009, and the valley appeared in the 1980s. At the same time, the hail disaster risk for cotton in the north of the North China Plain remained high, and the hail disaster risk in the cotton-planting areas in Xinjiang Uygur Autonomous Region, increased rapidly, so it is necessary to enhance preparedness.



(**a**) 1950–1959 (**b**) 1960–1969 (**c**) 1970–1979

(**d**) 1980–1989 (**e**) 1990–1999 (**f**) 2000–2009

Figure 6. Hail disaster risk for cotton over counties in China in each decade.

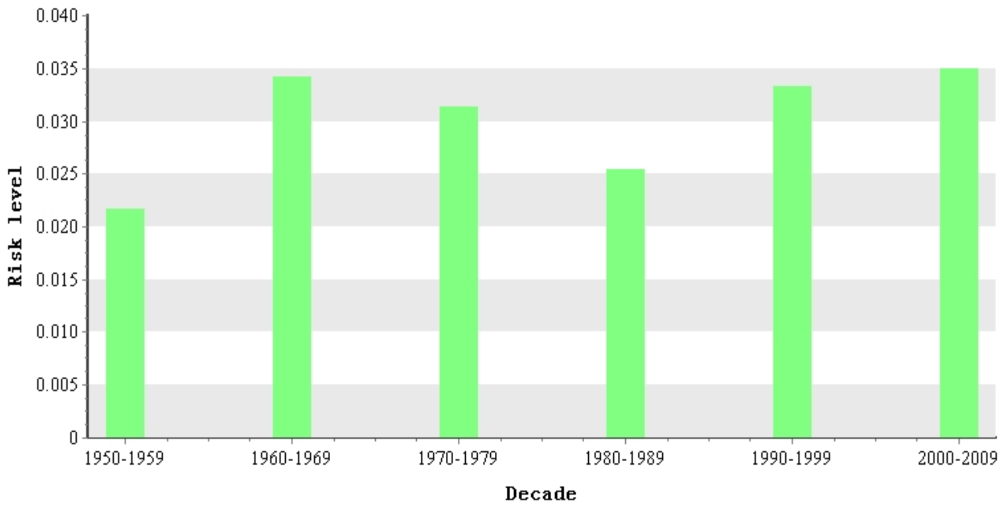


Figure 7. Interdecadal variation trend of hail disaster risk for cotton in China.

3.2.2. Interannual Variation

The interannual variation of the hail disaster risk for cotton over counties in China is shown in Figure 8. The yellow line indicates the average value of risk level. The red line is the trend line of hail disaster risk for cotton in China over 60 years.

The risk above the average is mainly distributed in the periods from the 1960s to the mid-1970s, the early and mid-1990s and the first decade of the 21st century. Before 1962, hail disaster risk for cotton showed fluctuations at a low level, and that in 1955 was above the average; from 1962–1974, hail disaster risk for cotton showed fluctuations at a high level, and only that in 1966 and 1970 was below the average; from 1975 to 2003, hail disaster risk for cotton showed fluctuations with a decreased amplitude around the average; from 2004 to 2009, cotton hail risk increased rapidly (the risk in 2004 was 0.1078), and, except in 2005 and 2009, that in other years kept higher than the average. The results show that the hail disaster risk for cotton in China shows an upward trend, with fluctuations on the whole. The maximum risk appeared in 2004, the minimum risk appeared in 1960.

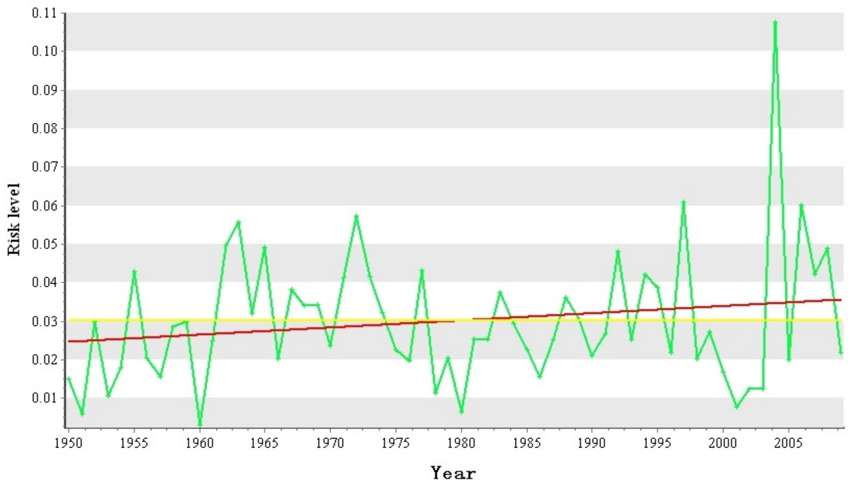


Figure 8. Interannual variation of the hail disaster risk for cotton over counties in China.

Mann-Kendall trend test also verifies such results (Figure 9). Thereof, the UF statistics from 1964 to 1977 is above critical line at 0.05 significance level, showing an obvious uptrend, which complies with the results of interannual and interdecadal analysis. Additionally, there are two abrupt change points in the 60 years, which are respectively 1951 (showing significant uptrend) and 2008 (showing significant downtrend). Previous studies [9,16,18] have concluded that hail days and hail disasters decreased in mainland China, while our results show the hail disaster risk for cotton gradually increased with fluctuations, although the future trends of hail disasters affecting cotton are unknown. This verifies that the studies on spatiotemporal pattern taking hail disaster as a whole do not necessarily reveal the laws of hail disasters to specific hail-affected bodies. Therefore, it is required to develop separate studies on hail disaster risk to the specific hail-affected bodies such as crops, buildings, and cars.

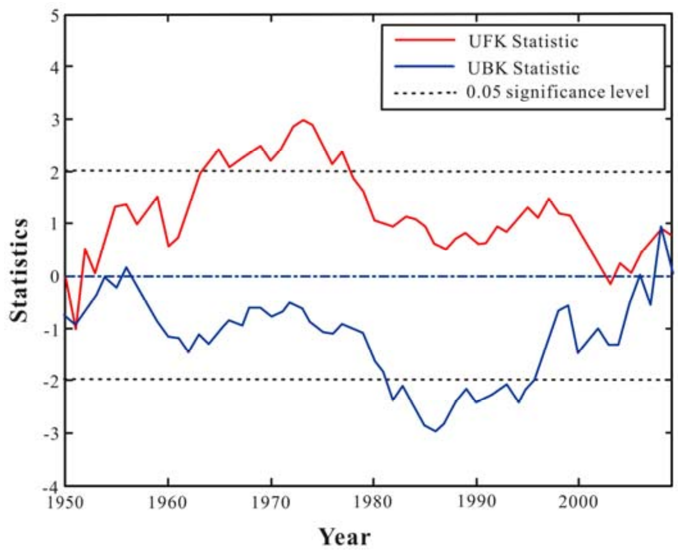


Figure 9. Mann-Kendall trend test of hail disaster risk for cotton in China.

3.2.3. Variation in the Growth Periods

With the variation of growth periods (sowing and seeding stage, seedling stage, bud stage, boll stage and boll opening stage) of cotton in China from seedling to harvest, the hail disaster risk shows movement from the south to the north. The areas with the highest hail disaster risk at the sowing and seeding stage are distributed in Southern China; since the seedling stage, the areas with the highest risk move northward to the central and Northern China and Southern Xinjiang Uygur Autonomous Region; since the bud stage, the areas with the highest risk continue to move northward, and are mainly distributed in the south of the Northeastern China, North China Plain and northern Xinjiang Uygur Autonomous Region; since the boll stage, the areas with the highest risk move northward again, and are mainly distributed in the north of North China Plain, Sichuan Basin and northern Xinjiang Uygur Autonomous Region, while the risk in other cotton-planting counties has little change; since the boll opening stage, the areas with the highest risk are concentrated in the north of the North China Plain, and the risk in other cotton-planting counties is relatively low. In one word, hail disaster risk varies with cotton-planting areas and growth periods. In Southern China and Sichuan Basin, the growth period with the highest risk is the sowing and seeding stage, followed by the boll stage; in central China and Southern Xinjiang Uygur Autonomous Region, the growth period with the highest risk is the seedling stage; in Northern China and northern Xinjiang Uygur Autonomous Region and in the south of Northeastern China, the growth period with the highest risk is the bud stage.

4. Discussion

4.1. Hail Disaster Risk for Cotton Assessment Method

Numerous studies have applied GIS to record, adjust and analyze hail disaster risk [10,65–73]. However, these studies failed to reveal the spatiotemporal laws of hail disaster risk for cotton because of shortcomings in the theoretical framework and methods.

We emphasize the exposure perspective of hail-affected bodies in order to achieve a reasonable hail disaster risk assessment. The exposure as attributed to hazard-affected bodies has long been recognized as an important element of risk that influences the risk assessment result directly [62,63]. For example, Zhou *et al.* [74] found that high exposure was a significant risk driver. The exposure analysis is mainly to determine the number of hazard-affected bodies and their spatiotemporal variation [76]. Additionally, the exposure varies with hazard-affected bodies [75]. Specifically, for cotton as the hail-affected body, the exposure includes its planting distribution and temporal variation, which refers to five growth stages. However, previous studies seldom took the spatiotemporal variation of hail-affected bodies, including cotton, into account [10,65–73]. We therefore proposed a revised risk model that is defined as a function of hail hazard, spatiotemporal exposure and vulnerability of hail-affected bodies. Because of the advance in the theoretical framework of risk, our method is more suitable for assessing the risk of hail disasters to cotton and other crops compared with the previous studies.

The effect of exposure on risk is complex. Lee *et al.* [11] concluded that the higher the exposure is, the higher the resilience becomes, which lowers the risk. But the conclusion is fit for the condition of population, since a higher population means more human resources for enhancing resilience. However, for cotton and the other crops, the conclusion might be wrong because crops cannot fight against disasters actively like humans do. On the contrary, the higher the cotton exposure to hail is, the higher the risk might be. Obviously, more efforts are needed to study the effect of exposure on risk.

The method proposed in this paper also avoids the subjectivity of the index weight setting in the previous studies. Most previous studies assessed the risk of hail disasters using three indices, which are sensitivity of the hazard-forming environment (sensitivity, usually regarded as a aspect of vulnerability [74]), hail hazard index (Hazard) and vulnerability of the hail-affected body (vulnerability) [69–73], and then assigned respective weights to sensitivity, hazard and vulnerability respectively as 0.3, 0.4 and 0.3 [69]; 0.3, 0.4 and 0.3 [70]; 0.3, 0.3 and 0.4 [71]; 0.3, 0.3 and 0.4 [72]; 0.3, 0.3 and 0.4 [73]; or 0.4761, 0.1604 and 0.3635 [66]. The assignments to contribution (weight) of the sensitivity, hazard and vulnerability are highly subjective. Therefore, our proposed method combines hazard, exposure and vulnerability into a integrated hail disaster risk index without weight assignment, therefore avoiding the adverse effect of subjectivity in risk assessment.

The application of historical hail disaster case data in risk assessment is another improvement of our method. Most studies attempted to use the number of hail days or hail frequency as the hazard index, making it impossible to reveal the real hail risk [2,9,10,12–30,65–73]. In this study, the datasets of historical hail disasters affecting cotton instead of hailfall events were used. With the support of GIS, we applied county as the assessment unit, while previous studies mostly focused on province [9,16–26,35–43,46,69–73], and a fine resolution (county unit) assessment at large-scale (national) achieved. The research results on the spatiotemporal pattern of hail disaster risk for cotton suggest that our proposed research ideas and methods are feasible to assess the hail disaster risk for cotton or other hail-affected bodies.

4.2. Hail Disaster Risk for Cotton in China and Its Policy Application

Although the risk level of hail disasters affecting cotton in China is low, more than 10% of the cotton-planting counties still face great risk of hail disasters. Moreover, Zhao *et al.* [9] found that the number of counties suffering from hail disasters showed a downward trend after 1987, and Zhang and Gao [16] also stated that the annual hail days in China decreased apparently in 1971 to 2000. Xie *et al.* [18] also found a similar trend.

However, our results showed that the hail disaster risk for cotton in China increased (Figures 8 and 9). Such difference in the spatiotemporal distribution of hail disasters affecting cotton with the hail events and hail disasters suggests that, under the same hail hazard, hail disaster risk is largely determined by the exposure and vulnerability of hail-affected bodies. Additionally, there are several driving forces of hail disaster risk for cotton, including climate change [17,18], change of cotton varieties, change of cotton-planting distribution, and so on. Since the hail events and hail disasters have decreased on the whole, the increase of hail disasters affecting cotton is possibly caused by the changes of planting distribution and varieties. Therefore, hail disaster risk is heavily influenced by the exposure and vulnerability of a specific hail-affected body.

Additionally, in terms of spatial distribution, although the areas with high hail disaster risk levels vary in different decades, the hail disaster risk for cotton in the north of the North China Plain, a traditional cotton-planting area, remains high. At the same time, the hail disaster risk in cotton-planting areas of Xinjiang Uygur Autonomous Region, a new and rapidly growing cotton-planting area, is increasing rapidly [36–39]. Since these two regions play a key role in cotton production in China, it is highly necessary to enhance the preparedness for hail disasters affecting cotton accordingly.

Furthermore, the hail disaster risk for cotton in China varies greatly with growth periods, and the descending order of risk level is bud stage, seedling stage, sowing and seeding stage, boll stage and boll opening stage. However, in different cotton-planting areas, the growth periods with the highest risk are different. In Southern China and Sichuan Basin, the highest risk appears at the sowing and seeding stage, followed by the boll stage; in central China and Southern Xinjiang Uygur Autonomous Region, the highest risk appears at the seedling stage; in Northern China and Northern Xinjiang Uygur Autonomous Region and Northeastern China, the highest risk appears at the bud stage. Although it shows that the bud stage of cotton has the highest vulnerability to hail strike [81], our results indicate that the highest risk level does not always appear at the bud stage .

Our findings indicate that the prevention plan of hail disasters affecting cotton plays a key role in achieving the sustainability of cotton production [83]. In addition, reasonable prevention and reduction measures for hail disasters affecting cotton should take both high-risk regions and key growth periods into account. The findings on the spatiotemporal pattern of hail disaster risk for cotton provide strong support for developing plans and countermeasures coping with hail disasters affecting cotton.

4.3. Limitations and Future Studies

Due to data limitations, this study uses the proportion of cotton field area in a county as the vulnerability index of cotton-planting counties. Therefore, the risk level of hail disasters affecting cotton is an indicator revealing the possibility of cotton loss caused by hail, which is a dimensionless variable, rather than the actual yield loss. The loss of agricultural productivity caused by hail is not included in the statistical year book of China. Some insurance companies have the data about crop losses caused by hail. Vinet [31], Changnon [32], Webb *et al.* [33], Sioutas *et al.* [34] and McMaster [67] studied hail disasters based on the data of insurance. Unfortunately, it is very difficult to get crop insurance data in China. Recently, some experimental studies have revealed the quantitative relationship between hail intensity and cotton damages [81,82]. Therefore, our future research could be improved based on data provided by hail disaster cases and field experiment jointly.

5. Conclusions

Understanding the spatiotemporal distribution pattern of hail disaster risk for cotton is crucial in mitigating hail disasters and promoting the sustainability of cotton farming. This paper suggests a theoretical framework and analytical procedure for assessing the risk of hail disasters to cotton, which are applied to assess the hail disaster risk for cotton in China. Some conclusions have been drawn.

(1) There is a need to distinguish the concepts of hailfall events and hail disasters. Furthermore, emphasis should be given to the exposure perspective of hail-affected bodies for achieving more accurate and reasonable hail disaster risk assessment for cotton.

(2) The methods for assessing the risk of hail disasters to cotton are suggested, using the data of hail disaster cases, and based on such indexes as hail disaster frequency, spatiotemporal exposure and vulnerability of cotton. With technical support of GIS, a comprehensive research framework is advocated.

(3) The hail disaster risk for cotton shows a gradually increasing trend from 1950 to 2009, with more than 10% of the counties in China facing great threat. The hail disaster risk for cotton remains high in the north of the North China Plain, and increases rapidly in the cotton-planting areas in Xinjiang Uygur Autonomous Region.

(4) The hail disaster risk for cotton in China shows a great difference across growth periods. The descending order of risk levels is bud stage, seedling stage, sowing and seeding stage, boll stage, and boll opening stage. The growth stage with the highest hail disaster risk level for cotton varies between different cotton-planting regions.

(5) The management of hail disaster risk for cotton in China should be enhanced. Strengthening prevention of the hail disaster risk in the key growth periods and high risk regions undoubtedly plays an important role in promoting the sustainable development of cotton production.

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References

1. Duan, Y. *Hail Disaster*; China Meteorological Press: Beijing, China, 2009. (In Chinese)
2. Baldi, M.; Ciardini, V.; Dalu, J.D.; Filippis, T.D.; Maracchi, G.; Dalu, G. Hail occurrence in Italy: Towards a national database and climatology. *Atmos. Res.* **2014**, *138*, 268–277. [CrossRef]
3. Lemons, H. Hail in American Agriculture. *Econ. Geogr.* **1942**, *18*, 363–378. [CrossRef]

4. Gall, M.; Borden, K.A.; Emrich, C.T.; Cutter, S.L. The Unsustainable Trend of Natural Hazard Losses in the United States. *Sustainability* **2011**, *3*, 2157–2181. [CrossRef]
5. Changnon, S.A., Jr.; Farhar, B.C.; Swanson, E.R. Hail Suppression and Society: Assessment of future hail suppression technology reveals its development should be sizable or ignored. *Science* **1978**, *200*, 387–394. [CrossRef] [PubMed]
6. Changnon, S.A. Increasing major hail losses in the U.S. *Clim. Chang.* **2009**, *96*, 161–166. [CrossRef]
7. Qin, D.H. Major meteorological disasters impacting on China and their development situation. *J. Nat. Dis.* **2007**, *16*, 46–48. (In Chinese)
8. Velten, S.; Leventon, J.; Jager, N.; Newig, J. What Is Sustainable Agriculture? A Systematic Review. *Sustainability* **2015**, *7*, 7833–7865. [CrossRef]
9. Zhao, J.T.; Yue, Y.J.; Wang, J.A.; Yin, Y.Y.; Feng, H.Y. Study on Spatio-temporal Pattern of Hail Disaster in China Mainland from 1950 to 2009. *Chin. J. Agrometeorol.* **2015**, *36*, 83–92. (In Chinese).
10. Berz, G.; Kron, W.; Loster, T.; Rauch, E.; Schimetschek, J.; Schmieder, J.; Siebert, A.; Smolka, A.; Wirtz, A. World map of natural hazards—A global view of the distribution, intensity of significant exposures. *Nat. Hazards* **2001**, *23*, 443–465. [CrossRef]
11. Lee, T.L.; Chen, C.H.; Pai, T.Y.; Wu, R.S. Development of a Meteorological Risk Map for Disaster Mitigation and Management in the Chishan Basin, Taiwan. *Sustainability* **2015**, *7*, 962–987. [CrossRef]
12. Giaiotti, D.; Nordio, S.; Stel, F. The climatology of hail in the plain of Friuli Venezia Giulia. *Atmos. Res.* **2003**, *67–68*, 247–259. [CrossRef]
13. Leslie, L.M.; Leplastrier, M.; Uckley, B.W. Estimating future trends in severe hailstorms over the Sydney Basin: A climate modelling study. *Atmos. Res.* **2008**, *87*, 37–51. [CrossRef]
14. Počakal, D.; Večenaj, Ž.; Štalec, J. Hail characteristics of different regions in continental part of Croatia based on influence of orography. *Atmos. Res.* **2009**, *93*, 516–525. [CrossRef]
15. Mezher, R.N.; Doyle, M.; Barros, V. Climatology of hail in Argentina. *Atmos. Res.* **2012**, *114*, 70–82. [CrossRef]
16. Zhang, F.H.; Gao, H. Temproal and spatial features of hail days in China. *J. Nanjing Inst. Meteorol.* **2008**, *31*, 687–693. (In Chinese)
17. Zhang, C.; Zhang, Q.; Wang, Y. Climatology of hail in China: 1961–2005. *J. Appl. Meteor. Climatol.* **2008**, *47*, 795–804. [CrossRef]
18. Xie, B.; Zhang, Q.; Wang, Y. Trends in hail in China during 1960–2005, Geophys. *Res. Lett.* **2008**, *35*, 195–209. [CrossRef]
19. Zhao, H.Y.; Ning, H.F.; Xu, J.F.; Dong, A.X.; Li, Q.Y. Temporal and spatial distribution characteristics of hail in northwest China. *Arid Meteorol.* **2005**, *23*, 37–40. (In Chinese)
20. Ye, C.H.; Jiang, H.F.; Li, N.; Zhai, Z.H.; Ding, Y.; Guo, W.L. Temporal and spatial characteristics of hail distribution in Beijing area. *J. China Agric. Univ.* **2007**, *12*, 34–40. (In Chinese)
21. Bao, Y.X.; Qin, W.N.; Gao, P.; Shen, S.H.; Jiang, Y.P. Spatiotemporal change patterns of hail disaster in Jiangsu Province during recent 30 years. *J. Nat. Dis.* **2012**, *21*, 197–205. (In Chinese)
22. Cai, Y.Y.; Wang, H.; Yu, Y.J. Spatiotemporal distribution and weather characteristics of hail in Fujian Province. *J. Nat. Dis.* **2009**, *18*, 43–48. (In Chinese)
23. Zhang, Z.; Lin, L.; Feng, R.P.; Yang, K. Characteristics of temporal and spatial distribution of hails in Ningxia. *Meterol. Sci. Technol.* **2008**, *36*, 567–569. (In Chinese)
24. Wang, X.M.; Ni, H.; Zhou, S.X. Analysis on distribution law character in time and space of hail disasters in Jilin Province. *J. Catastrophol.* **1999**, *14*, 51–55. (In Chinese)
25. Yang, J.K.; Qi, M.H. Temporal and spatial characteristics of hail distribution in Yunnan Province. *Meteorol. Sci. Technol.* **2005**, *33*, 41–44. (In Chinese)
26. Zhou, Y.S.; Wang, C. Characteristics of temporal and spatial distribution of hail in Guizhou Province. *J. Guizhou Meterol.* **2009**, *33*, 9–11. (In Chinese)
27. Zhang, D.M.; Zhang, X.; Zhao, Z.Y. Temporal-spatial distribution of hail in Fuxin City during 1977 to 2009. *J. Anhui Agric.* **2010**, *38*, 17587–17589. (In Chinese)
28. Xu, Y.X.; Wang, H.B.; Tan, Z.M. Temporal and spatial distribution characteristics and defensive countermeasures of hail in Yaozhou Tongchuan. *J. Shaanxi Agric. Sci.* **2008**, *2*, 165–167. (In Chinese)
29. Gu, X.; Zhang, Y.M. The inhomogeneity characteristics of hail events in the year in southeast Guizhou. *Chin. J. Agro-Meteorol.* **2010**, *31*, 627–632. (In Chinese)

30. Cao, L.X.; Liu, X.Q.; Zhang, L.; Wamg, Z.L.; Zhang, J.D. Temporal and spatial distribution characteristics and defensive countermeasures of hail from 1998 to 2008 in Akesu. *Desert Oasis Meteorol.* **2009**, *3*, 21–24. (In Chinese)
31. Vinet, F. Climatology of hail in France. *Atmos. Res.* **2001**, *56*, 309–323. [CrossRef]
32. Changnon, S.A. Temporal, spatial distributions of damaging hail in the continental United States. *Phys. Geogr.* **2008**, *29*, 341–350. [CrossRef]
33. Webb, J.D.C.; Elsoma, D.M.; Meadena, G.T. Severe hailstorms in Britain and Ireland, a climatological survey and hazard assessment. *Atmos. Res.* **2009**, *93*, 587–606. [CrossRef]
34. Sioutas, M.; Meaden, T.; Webb, J.D.C. Hail frequency, distribution, intensity in Northern Greece. *Atmos. Res.* **2009**, *93*, 526–533. [CrossRef]
35. Wang, J.A.; Shi, P.J.; Liu, Y.H.; Fang, W.H. Hail disaster in China during 1990–1996 and its dynamic spatial and temporal analysis. *J. Nat. Dis.* **1999**, *8*, 46–53. (In Chinese)
36. Wang, Q.X.; Ren, Y.Y. Temporal and spatial distribution features of hail disasters in Xinjiang in recent 51 years. *Arid Land Geogr.* **2006**, *29*, 65–69. (In Chinese)
37. Resul, A.; Wahit, E.; Melike, S.; Wang, M.Y. Analysis of space-temporal distribution of hail Disaster and its statistics character in Kuitun-Manas River Basin. *Desert Oasis Meteorol.* **2007**, *1*, 37–40. (In Chinese)
38. Mansur, S. Analyzing the spatio-temporal variations of hail disasters in Southern Xinjiang region during recent 60 years. *J. Glaciol. Geocryol.* **2012**, *34*, 795–801. (In Chinese)
39. Resuli, A.; Niu, S.J.; Wang, H.Y. Spatial temporal distribution characteristics of hail in Xinjiang. *J. Nat. Dis.* **2013**, *22*, 158–163. (In Chinese)
40. Liu, X.M.; Li, J.; Dai, P.; Liu, M.; Wei, N.; Liu, F.H.; Huang, X.P.; Guo, Y.J. Temporal-spatial distribution of hail disaster from 1951 to 2008 in Liaoning province. *J. Meteorol. Environ.* **2009**, *25*, 24–26. (In Chinese)
41. Yao, J.Y.; Sun, S.; Liu, Y.X.; Wang, C.L.; Zhu, H.R. Analysis on temporal and spatial distribution characteristics of hail disasters in Heilongjiang Province. *Heilongjiang Agric. Sci.* **2012**, *4*, 45–49. (In Chinese)
42. He, T.R.; Ji, T.; Yang, H. Temporal and spatial distribution characteristics of hail disasters in the past 110 years in Chongqing. *J. Chongqing Norm. Univ. Nat. Sci.* **2013**, *30*, 22–25. (In Chinese)
43. Zhang, H.Z.; Jia, L. Temporal-spatial characteristics and hazard regionalization of hail events in Tibet. *Meteorol. Sci. Technol.* **2007**, *35*, 53–56. (In Chinese)
44. Zhou, L.; Yue, Y.J.; Li, J.; Qiu, M.M.; Shang, Y.R. Review of research on vulnerability assessment of hail hazard bearing body. *Chin. J. Agrometerol.* **2014**, *35*, 330–337. (In Chinese)
45. Yu, S.X.; Wang, Z.S. On the future Chinese cotton technological development strategy. *J. Shenyang Agric. Univ. Soc. Sci. Ed.* **2012**, *14*, 3–10. (In Chinese)
46. Wang, Y.; Wang, J.A.; Wu, W.B.; Li, W.H. Agricultural hail disaster and its seasonal regionalization in China. *J. Nat. Dis.* **2002**, *11*, 30–36. (In Chinese)
47. Wan, Y.X.; Jin, W.P.; Wang, G.E.; Li, H.H.; Cui, S.F.; Li, J.L. Study on growing of different type of cotton destroyed by hail-stones during Cotyledon Period. *China Cotton* **2004**, *31*, 12–13. (In Chinese)
48. Wen, K.G. *Encyclopedia of Meteorological Disasters in China*; China Meteorological Press: Beijing, China, 2006.
49. China Meterological Administration. *China Meteorological Disasters Yearbook 2006*; China Meteorological Press: Beijing, China, 2006. (In Chinese)
50. China Meterological Administration. *China Meteorological Disasters Yearbook 2007*; China Meteorological Press: Beijing, China, 2007. (In Chinese)
51. China Meterological Administration. *China Meteorological Disasters Yearbook 2008*; China Meteorological Press: Beijing, China, 2008. (In Chinese)
52. China Meterological Administration. *China Meteorological Disasters Yearbook 2009*; China Meteorological Press: Beijing, China, 2009. (In Chinese)
53. China Meterological Administration. *China Meteorological Disasters Yearbook 2010*; China Meteorological Press: Beijing, China, 2010. (In Chinese)
54. National Disaster Reduction Center of the Ministry of Civil Affairs of China (NDRC-MCA). *Disaster Reduction in China*; NDRC-MCA: Beijing, China, 2001.
55. National Disaster Reduction Center of the Ministry of Civil Affairs of China (NDRC-MCA). *Disaster Reduction in China*; NDRC-MCA: Beijing, China, 2002. (In Chinese)
56. National Disaster Reduction Center of the Ministry of Civil Affairs of China (NDRC-MCA). *Disaster Reduction in China*; NDRC-MCA: Beijing, China, 2003. (In Chinese)

57. National Disaster Reduction Center of the Ministry of Civil Affairs of China (NDRC-MCA). *Disaster Reduction in China*; NDRC-MCA: Beijing, China, 2004. (In Chinese)
58. Zhou, L.S.; Zhang, L.S.; Zhou, S.Y. *The Agriculture Atlas of People's Republic of China*; Sino Maps Press: Beijing, China, 1989. (In Chinese)
59. Institute of Cotton Research of Chinese Academy of Agricultural Sciences. *China Cotton Cultivation Science*; Shanghai Scientifi & Technical Publishers: Shanghai, China, 2013. (In Chinese)
60. Data Center for Resources and Environmental Sciences (RESDC) of Chinese Academy of Sciences. Land Use of China. 2005. Available online: http://www.resdc.cn/data.aspx?DATAID=98 (assessed on 1 January 2016).
61. Birkmann, J. Risk. In *Encyclopedia of Natural Hazards*; Bobrowsky, P.T., Ed.; Springer: Heidelberg, Germany, 2013.
62. United Nations Office for Disaster Risk Reduction. *Living with Risk: A Global Review of Disaster Reduction Initiatives*; United Nations: Geneva, Switzerland, 2004.
63. Dilley, M.; Chen, R.S.; Deichmann, U.; Lerner-Lam, A.L.; Arnold, M.; Agwe, J.; Buys, P.; Kjekstad, O.; Lyon, B.; Yetman, G. *Natural Disaster Hotspots: A Global Risk Analysis*; Disaster Risk Management Series No. 5; The World Bank: Washington, DC, USA, 2005.
64. Webb, J.D.C.; Elsom, D.M.; Meaden, G.T. The TORRO hailstorm intensity scale. *J. Meteorol.* **1986**, *11*, 337–339.
65. Wen, H.Y.; Tian, H.; Tang, W.A.; Lu, Y.Y.; Wu, R. Climatic characteristics of hail disaster and its risk zoning in Anhui Province. *Chin. J. Agrometeorol.* **2013**, *34*, 88–93. (In Chinese)
66. Dong, P.J.; Wang, J.J. Risk assessment model and regionalization of hail disaster in Beijing area. *Torrential Rain Dis.* **2012**, *31*, 29–34. (In Chinese)
67. Mcmaster, H. Hailstorm risk assessment in rural New South Wales. *Nat. Hazards* **2001**, *24*, 87–196. [CrossRef]
68. Leigh, R.; Kuhnel, I. Hailstorm Loss Modelling and Risk Assessment in the Sydney Region, Australia. *Nat. Hazards* **2001**, *24*, 171–185. [CrossRef]
69. Li, M.; Zhu, Y.; Ji, W.J. Risk evaluation of hail disaster in Yunnan tobacco planting areas based on GIS. *Chin. J. Agrometeorol.* **2012**, *33*, 129–133. (In Chinese)
70. Hu, H.B.; Dong, P.J.; Xiong, Y.J.; Xuan, C.Y. Hail risk evaluation of meteorological disaster during Beijing olympic games. *Meteorol. Mon.* **2008**, *34*, 84–89. (In Chinese)
71. Dong, P.J.; Wu, Z.H. Risk evaluation model on hail disaster during the Beijing olympic games. *Torrential Rain Dis.* **2008**, *27*, 104–108. (In Chinese)
72. Luo, P. GIS-based risk evaluation model of meteorological disaster: A case study on hail disaster in Chongqing administrative region. *J. Nat. Dis.* **2007**, *16*, 38–44. (In Chinese)
73. Li, L.H.; Chen, H.W.; Mao, W.Y.; Zuo, M.; Liu, W.J. GIS-based hail risk zonation and assessment in Aksu prefecture. *Arid Zone Res.* **2010**, *27*, 224–229. (In Chinese) [CrossRef]
74. Zhou, Y.; Liu, Y.S.; Wu, W.X.; Li, N. Integrated risk assessment of multi-hazards in China. *Nat. Hazards* **2015**, *78*, 257–280. [CrossRef]
75. Jenks, G.F. The Data Model Concept in Statistical Mapping. *Int. Yearb. Cartogr.* **1967**, *7*, 186–190.
76. Wei, F.Y. *Modern Climate Statistical Diagnosis and Prediction Technology*; China Meteorological Press: Beijing, China, 1999. (In Chinese)
77. Fu, C.B.; Wang, Q. The definition and detection of the abrupt climatic change. *Sci. Atmos. Sin.* **1992**, *16*, 482–493. (In Chinese)
78. Ren, G.Y. *Climate Change and Chinese Water Resources*; China Meteorological Press: Beijing, China, 2007. (In Chinese)
79. Zhang, X.R.; Wang, Z.B.; Lin, J. GIS based measurement and regulatory zoning of urban ecological vulnerability. *Sustainability* **2015**, *7*, 9924–9942. [CrossRef]
80. Li, M.Z.; Zhao, F.X. The influence of cotton growth and yield under different hail disaster. *Anhui Agric. Sci.* **2006**, *34*, 649–673. (In Chinese)
81. Hu, G.F.; Qiu, M.M.; Zhou, L.; Li, J.L.; Shen, Y.N.; Yue, Y.J. Experimental study on cotton vulnerability to hail hazard: The effect of simulated hailfall on cotton damages. *J. Nat. Dis.* **2015**, *24*, 139–148. (In Chinese)

82. Yue, Y.J.; Li, J.; Hu, G.F.; Zhou, L.; Zhang, F.; Zhang, H.; Zhao, J.T. Equipment and methodology for experimental research of cotton vulnerability to hail hazard. *J. Catastrophol.* **2015**, *30*, 102–107. (In Chinese)
83. Vitale, J.; Ouattarra, M.; Vognan, G. Enhancing Sustainability of Cotton Production Systems in West Africa: A Summary of Empirical Evidence from Burkina Faso. *Sustainability* **2011**, *3*, 1136–1169. [CrossRef]