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Spatial-temporal pattern changes of main agriculture natural disasters in China during 1990–2011

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Abstract: China is a disaster prone country, and a comprehensive understanding of change of disasters is very important for China's agricultural development. In this study, statistical techniques and geographic information system tools are employed to quantify the main agriculture disasters changes and effects on grain production in China during the period of 1990–2011. The results show that China's grain production was severely affected by disasters including drought, flood, hail, frost and typhoon. The annual area covered by these disasters reached up to 48.7×10^6 ha during the study period, which accounted for 44.8% of the total sown area, and about 55.1% of the per unit area grain yield change was caused by disasters. In addition, all of the disasters showed high variability, different changing trends, and spatial distribution. Drought, flood, and hail showed significantly decreasing trends, while frost and typhoon showed increasing trends. Drought and flood showed gradual changes and were distributed across the country, and disasters became more diversified from north to south. Drought was the dominated disaster type in northern China, while flood was the most important disaster type in the southern part. Hail was mainly observed in central and northern China, and frost was mainly distributed in southern China. Typhoon was greatly limited to the southeast coast. Furthermore, the resilience of grain production of each province was quite different, especially in several major grain producing areas, such as Shandong, Liaoning, Jilin and Jiangsu, where grain production was seriously affected by disasters. One reason for the difference of resilience of grain production was that grain production was marginalized in developed provinces when the economy underwent rapid development. For China's agricultural development and grain security, we suggest that governments should place more emphasis on grain production, and invest more money in disaster prevention and mitigation, especially in the major grain producing provinces.

Keywords: spatial-temporal pattern; grain production; disasters; China

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1 Introduction

Global climate change has received increasing attention in recent years (Houghton *et al*., 2001). It has been acknowledged that natural disasters are likely to become more frequent, more severe, and sustained along with climate change (Easterling, 2000; McMichael *et al*., 2006; Morrissey and Reser, 2007; Xiao and Xiao, 2010). For example, there is a drying trend in Sahel (Held *et al*., 2005) and more severe droughts are likely to occur in the future in the United States (Woodhouse and Overpeck, 1998), while Delgado *et al*. (2010) pointed out that extreme floods showed an increasing trend in the Mekong River in the past decades. Natural disasters can significantly hinder human and economic development (McMichael *et al*., 2006; Morrissey and Reser, 2007; Kim *et al*., 2013; Ni *et al*., 2010). According to data from the Center for Research on the Epidemiology of Disasters (CRED), since 1980 the top three wind storm disasters resulted in more than 160 thousand deaths. The total losses caused by flood during 1970–2006 in Europe amounted to US $140 billion (Barredo, 2009). In addition, losses resulting from natural disasters have grown steadily with time (Kunkel *et al*., 1999; Changnon *et al*., 2000; Greenough *et al*., 2001). Agricultural production is dependent on natural resources, which makes it more vulnerable to natural disasters, such as drought, flood, hail and frost, as compared with other industries (Lambert and Parker, 1998; Sivakumar, 2006; Iglesias *et al*., 2011). In particular, drought and flood are widely distributed across the world. Edmeades (2013) reported that drought in the midwest US caused a reduction of 15% in national maize production in 2012. Wet rice production was also significantly affected by flood in Vietnam (Chau *et al*., 2013). In brief, natural disasters are a major threat factor to the sustainable development of grain production.

Due to its complex geographical environment, China is acknowledged as one of the most vulnerable countries in the world to disasters (Liu and Diamond, 2005; Xiao and Xiao, 2010). The main disaster types include drought, flood, earthquake, landslide and storm (Wang *et al*., 1995; Liu and Diamond, 2005; Zhou *et al*., 2013). Wang *et al*. (1995) discussed the spatial characteristics of natural disasters in China, and found that the Huang-Huai-Hai region experienced the most serious economic losses by natural disasters among all regions, while the border zone of Yunnan-Shichuan-Guizhou-Guangxi underwent the highest number of casualties. In total in China, there were annual averages of 4840 people killed and about US $3.41 billion in direct economic loss caused by major natural disasters during the period of 1990–2011 (Zhou *et al*., 2013). In particular, the 1998 floods of the Yangtze River caused thousands of deaths and more than US $18 billion in direct economic losses (Wang *et al*., 1999). Previous studies have shown that China's grain yield was sensitive to natural disasters (Lambert and Parker, 1998; Simelton, 2011; Chen *et al*., 2008). Wang *et al*. (2012) found that grain loss by disasters was about 55.4 million tons, accounting for 10.4% of the total grain yield in 2009. Thus it is critical for China to maintain stable grain production, as the population of China accounts for more than 20% of the world's population (Qiang *et al*., 2013). The effects in grain production by natural disasters have drawn great attention from scholars. Liu and Diamond (2005) reported that about 160,000 km^2 of cropland were damaged by drought in China, and the drought affected area showed an increasing trend (Li *et al*., 2009; Liu, 2012; Qiu *et al*., 2013). The flood situation is also becoming more severe (Jia and Pan 2013). Therefore, it is necessary to understand the spatial-temporal pattern change of natural disasters. However, most of the previous studies have concentrated on a certain type of natural disasters (Zhang, 2004; Li *et al*., 2009; Xiao and Xiao, 2010; Liu, 2012; Qin *et al*., 2013) or disasters which caused serious casualties (Zhou *et al*., 2013), and few studies have explicitly explored the spatial dynamics of natural disasters and their effects on grain production. In this paper, we analyzed the trends and spatial changes of major disasters from 1991 to 2011 and their influence on grain production. The study results may provide support for policy makers to mitigate natural disasters and ensure the stable development of agricultural production.

2 Data sources and methods

2.1 Data sources

In this paper, disaster data was obtained from China Agriculture Statistical Report, sown area data and grain yield data were obtained from China Statistical Yearbook. All of the statistical yearbooks were compiled by the Chinese official agencies and other authoritative agencies, for every year from 1990 to 2011 at the provincial scale.

Due to data availability issues, Hong Kong, Macao and Taiwan are excluded. In addition, the data of Chongqing was added to Sichuan Province, as its data from before 1997 are unavailable. Among these provinces and municipalities, Beijing, Shanghai and Tianjin are municipalities, which are characterized by high degrees of urbanization and industrialization. Liaoning, Hebei, Shandong, Jilin, Inner Mongolia, Jiangxi, Hunan, Sichuan, Henan, Hubei, Jiangsu, Anhui and Heilongjiang are the major grain producing areas, the grain yield of which accounts for more than 75% of China's total grain yield. According to the statistical yearbooks, grain production was mainly affected by drought, flood, hail, frost and typhoon. Therefore, here we focus on these five types of disasters, and the data include disaster area, sown area and grain yield. Meanwhile, in order to eliminate the impact of sown area change, the ratio of disaster area to sown area was used to quantify the disaster change. All data were input to the geographic information system (GIS).

2.2 Methods

2.2.1 Changing trend analysis

Various techniques have been developed in previous studies to detect the trend of time series (Hirsch *et al*., 1991; Yu *et al*., 1993; Xu *et al*., 2005), and the changing trends of disasters were analyzed by the collected time series data. In this paper, the Mann-Kendall (M-K) test was employed to analyze the disaster changing trend. The M-K test is acknowledged as an effective tool for identifying whether or not trends exist in the time series data, and has been widely used in different fields. For a time series, the M-K test statistics can be defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{1}$$

where

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} 1 & x_j - x_i > 0 \\ 0 & x_j - x_i = 0 \\ -1 & x_j - x_i < 0 \end{cases} \tag{2}$$

and x_i and x_j are the disaster area in time i and j, n is the number of samples. S will be positive if there is an increasing trend and negative if there is a decline trend. The significance of the trend can be calculated by comparing the standardized variable Z in Eq. (3) with the standard normal variable at the expected significance level P.

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \tag{3}$$

Furthermore, the magnitude of the change trend can be quantified by Eq. (4).

$$\alpha = Median\left(\frac{x_j - x_i}{j-i}\right) \tag{4}$$

where $1 < i < j < n$ and α is the trend magnitude. At an expected significance level, negative values indicate a decreasing trend, while positive values indicate an increasing trend.

Generally speaking, disaster area fluctuated significantly with time. In this paper, the coefficient of variation (CV) was employed to analyze the overall change of disaster. The CV can quantify the variability of a series of numbers independent of their unit and mean, and it can also be used to compare the variability among different series. It is defined as the ratio of the standard deviation σ of the series data to the mean μ (Eq.(5)).

$$\mathrm{CV} = \sigma / \mu \tag{5}$$

2.2.2 Spatial pattern change

The spatial distributions of disasters are uneven, thus it is necessary to quantify the spatial pattern changes of disasters. Previous studies have shown that spatial statistical approaches may improve our understanding of spatial-temporal dynamics (Getis and Ord, 1992; Anselin, 1995). In our study, Moran's I and Getis-Ord Gi* are employed to evaluate the spatial pattern of disasters. Moran's I is the most commonly used to measure the degree of spatial concentration or dispersion of disasters at a global scale, the index of which ranges from –1 to 1 (Eq.(6)).

$$I = \frac{n}{s} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} \omega_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{6}$$

where n is the number of observations, s is the aggregate of all spatial weights, x_i and x_j are the observations for area i and j, $\bar{x}$ is the mean of observations, and ω_{ij} is the spatial weight between area i and j. Negative values indicate dispersed patterns or negative spatial autocorrelation, while positive values indicate clustered patterns or positive spatial autocorrelation. In particular, value −1 indicates perfect dispersion, value 1 indicates perfect cluster, and value 0 indicates a random spatial pattern (Diniz *et al*., 2003).

Getis-Ord Gi* can generate a Z-score, which describes the degree of clustering of either high or low values, and has been widely used to detect hot spots and cold spots of disasters (Myint *et al*., 2007; Cheng and Yuqi, 2009). Furthermore, the results of Getis-ord Gi* were reclassified to four classes by the natural break method, including hot spots, sub-hot spots, cold spots and sub-cold spots. The spatial pattern change analysis was conducted in ArcGIS 9.3.

2.2.3 Linear regression model

Linear regression model is widely used to evaluate the relationship between two variables. Generally speaking, a set of observed data is known to be the dependent variable, another set is called to be the explanatory variable. The model can be expressed as follows,

$$y = \alpha + \beta x \tag{7}$$

where y is the dependent variable, x is the explanatory variable, α is the intercept, β is the regression coefficient. The strength of the linear association between the two variables is commonly quantified by the correlation coefficient, which is known as R^2. The value of R^2 is between 0 and 1, indicating the strength of the association of the observed data for the two variables. However, the R^2 value is affected by the number of explanatory variable. In this paper, we use the adjusted R^2 to replace R^2, which eliminates the influence of the number of explanatory variable, and it can be calculated by Eq. (8).

$$R^2_{adjust} = 1 - \frac{n-1}{n-k-1}(1-R^2) \tag{8}$$

where n is the number of observed data, and k is the number of explanatory variable.

3 Results and discussions

3.1 Changes of disasters

As shown in Figure 1, China's grain production was severely affected by natural disasters. Especially in 1991, the disaster area was about 83.2×10^6 ha, accounting for 74.1% of the sown area. The annual disaster coverage area reached up to 48.7×10^6 ha during the period of 1990–2011, accounting for 44.8% of the sown area. Meanwhile, the disaster coverage area fluctuated significantly, with CV being as high as 0.21. As can be seen from the figure, drought was the most serious disaster type, accounting for about 50.9% of the annual disaster area. Flood was the second major disaster type, with 26.7% of the annual disaster area. Hail and frost accounted for 9.7% and 9.8% of the annual disaster, respectively. The area affected by typhoon was quite small, with 2.9% of the annual disaster area. The trend of disaster coverage area showed a decreasing trend (Table 1), and the results calculated from

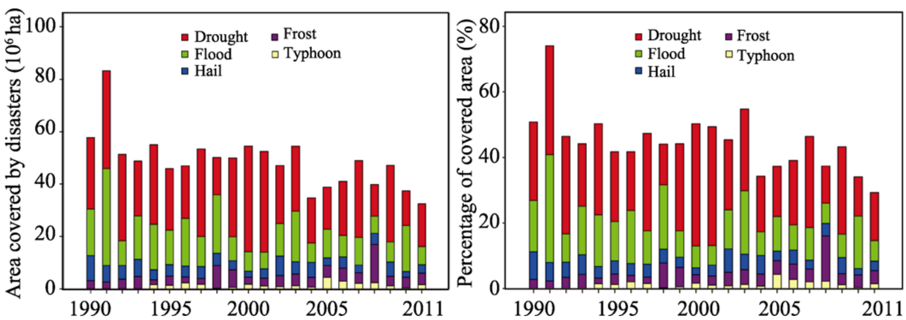

Figure 1 Disaster change from 1990 to 2011 in China

Table 1 M-K tests of disasters change of China

Type	Total	Drought	Flood	Hail	Frost	Typhoon
Disaster area	–0.498*	–0.342*	–0.385*	–0.342*	0.307*	0.033
Ratio of disaster area	–0.437*	–0.307*	–0.351*	–0.325*	0.299	0.033
CV of disaster area	0.21	0.34	0.54	0.37	0.61	0.66

Note: *, P=0.05.

disaster area and the ratio of disaster area to sown area (ratio of disaster area) were basically the same, which showed the results were credible. According to Table 1, the area covered by each disaster type showed different changing trends. Drought, flood and hail showed decreasing trends, while frost and typhoon showed increasing trends. Furthermore, the interannual variability of each disaster type was quite different. Typhoon had the maximum annual variation, followed by frost and flood, of which the CVs were 0.66, 0.61 and 0.54, respectively. The CVs of drought and hail were also high, being 0.34 and 0.37. The higher CVs indicated that the disaster had high variability and less stability, which would increase the grain production instability.

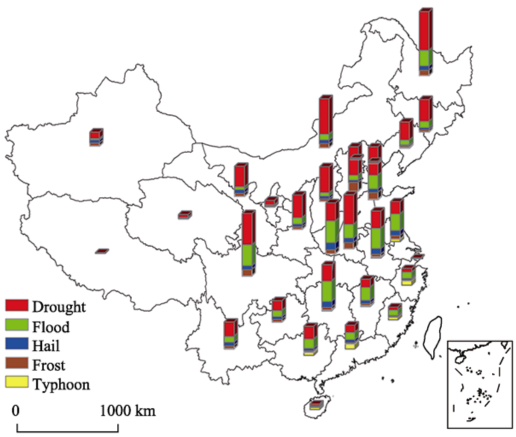

Figure 2 Annual composition of disasters of each province during 1990–2011

In terms of each province, the composition of disasters showed a gradual change from north to south and from west to east (Figure 2). Provinces in the north and west were dominated by drought, especially in Inner Mongolia and Shaanxi, where drought accounted for more than 70% of total disasters. The proportion of drought decreased from north to south and from west to east, while the other disaster types increased, and flood became the most important disaster in the east and south. Meanwhile, disasters became diversified from north to south. The CVs of drought and flood showed trends which are opposite to their compositions. The CV of flood was larger than that of drought in drought dominated provinces, while that of drought was larger than flood in flood dominated provinces. This further confirms the fact that the north mainly faces drought threat and the south faces flood threat throughout all time periods.

The disaster areas not only exhibited highly interannual variability, but were also uneven in terms of spatial distribution. Figure 3 describes the spatial distribution of the overall disaster area in the past 22 years. It is clear that the distribution of disasters possesses significant geographical distribution characteristics. Drought in northern China was more severe than that in southern China, and covered a larger area than other disaster types. The main reason for this is that the geographical distribution of water resources and cropland in China is uneven and mismatched. Khan *et al*. (2009) pointed that about 81% of China's water resources are distributed in southern China, while more than 64% of croplands are located in the northern part. Due to their sown areas, Xinjiang and Tibet were classified as cold spot areas, thus it was not indicated that their grain productions were less affected by drought.

The distribution of flood was opposite to that of drought. All hot spot areas of flood were distributed within four provinces in southern China, namely Hunan, Jiangxi, Zhejiang and Fujian. Grain production in central and northern China was more affected by hail than in other areas. Although the average annual temperature of southern China was much higher than that in the northern (Fan *et al*., 2011), frost in the south was more severe than in the north. This was mainly due to the fact that the temperature in winter in the north was too low for seeding. Similar to the distribution of flood, typhoon was largely limited to the southeast coast of China. Generally speaking, the hot spot and sub-hot spot areas of disasters were mainly distributed in central, eastern and northeastern China. All cold spot areas were concentrated in western China, while sub-cold spot areas were dispersed throughout north and south China.

For the interannual instability, the spatial pattern of disasters also changed along with time. Table 2 shows the Moran's I change during the study period. As mentioned in Section

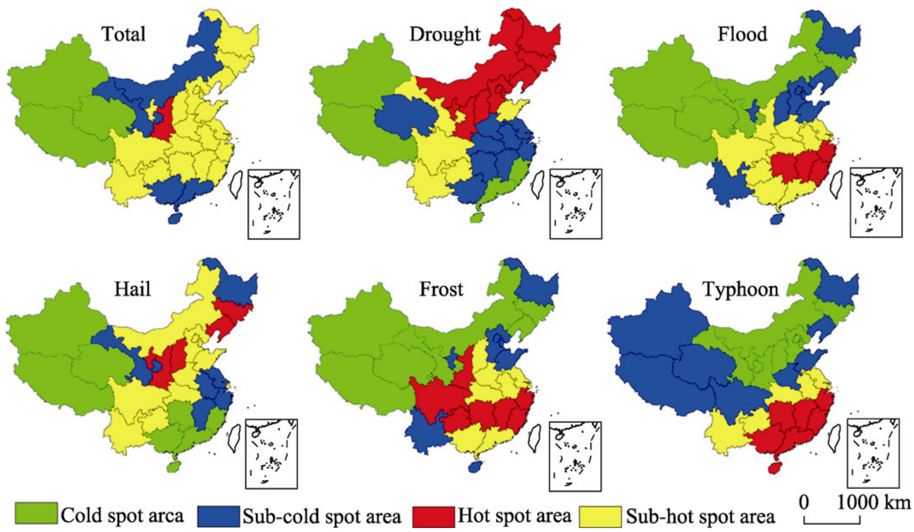

Figure 3 Spatial pattern of the overall disasters during 1990–2011

Table 2 Moran's I change from 1990 to 2011

Year	Total	Drought	Flood	Hail	Frost	Typhoon	Year	Total	Drought	Flood	Hail	Frost	Typhoon
1990	0.06	0.27*	0.06	–0.07	0.13*	–	2001	–0.01	–0.85	0.21*	0.21*	0.03	0.13*
1991	0.08	0.07	0.12*	–0.13	–0.10	–	2002	–0.10	0.15*	0.27*	–0.07	–0.03	0.14*
1992	–0.06	0.13*	0.24*	–0.10	0.09	–	2003	–0.04	–0.07	0.12	–0.17*	0.05	0.12*
1993	–0.10	0.13*	0.02	–0.14	0.03	–	2004	–0.00	–0.19*	0.12*	–0.06	0.05	0.07
1994	–0.05	0.07	0.09	–0.02	0.10	0.11*	2005	0.10	0.11	0.05	0.01	0.23*	0.27*
1995	–0.02	–0.03	0.11	–0.09	0.07	0.18*	2006	–0.09	0.01	0.07	–0.12	–0.04	0.28*
1996	–0.06	0.14*	0.06	–0.03	0.25*	0.23*	2007	0.02	–0.13	0.12	–0.06	0.18	0.16*
1997	–0.30*	0.02	0.19*	–0.06	–0.01	0.09	2008	0.14*	–0.08	0.20*	–0.10	0.26*	0.15*
1998	0.11	0.13*	0.11	–0.2*	0.16*	0.12*	2009	0.00	–0.06	–0.02	–0.10	–0.08	0.14*
1999	–0.07	0.13*	0.30*	–0.11	0.03	0.10*	2010	0.04	0.07	0.16*	–0.08	–0.01	0.15*
2000	0.02	–0.05	0.07	–0.03	0.28*	0.06	2011	0.07	0.12*	0.05	–0.01	0.29*	0.15*

Note: *, P=0.05; –, No data

2.2.2, the value ranging from 1 to –1 indicates that the spatial pattern was either clustered, random or dispersed. In other words, the values of Moran's I varied from year to year, indicating that the spatial pattern was constantly changing. In terms of specific disaster type, drought, flood and frost showed relatively clustered patterns, and especially in several certain years the value of Moran's I reached 0.30 and passed the 5% significance test. Hail mainly showed random patterns, except in 1998, 2001 and 2003, when it showed significantly dispersed and clustered patterns, respectively. Contrary to hail, typhoon showed a predominantly clustered pattern. Generally speaking, the spatial pattern of total disasters showed random patterns throughout the period of 1990–2011. However, the spatial pattern of each year was quite different, and the values of Moran's I ranged from –0.30 to 0.14, which indicated a significantly dispersed pattern and clustered pattern, respectively.

Meanwhile, the changing trend of disasters of each province was different. As shown in Figure 4 (as data of typhoon were not successive and mainly distributed in several provinces, M-K tests of typhoon in each province were not performed), the total disaster areas of most of the provinces showed declining trends, with the exceptions of Xinjiang, Yunnan, Inner Mongolia and Heilongjiang, which showed increasing trends. Xinjiang and Yunnan showed particularly significant increasing trends. Meanwhile, all disaster types showed increasing trends in Xinjiang and Heilongjiang. In addition, it should be noted that Heilongjiang was one of the major grain producing areas. In terms of the specific disaster type, drought showed increasing trends in Xinjiang, Tibet, Inner Mongolia, Yunnan, Heilongjiang and Jilin. Flood showed increasing trends in Xinjiang, Heilongjiang, Hunan and Hubei. Hail also showed increasing trends in Xinjiang and Heilongjiang. Different from the other disaster types, frost showed increasing trends in most of the provinces, except seven provinces where it showed decreasing trends.

Potential area covered by disasters was affected by the sown area. The trend of ratio of disaster area was slightly different when considering sown area. For example, drought in Heilongjiang and Tibet changed from an increasing trend to a declining trend, flood in Guangxi and Qinghai changed from decreasing to increasing trend, and the trends of hail and frost also changed to the opposite in several provinces. Overall, the greatest differences were located in Heilongjiang and Guangxi, where the trends changed to the opposite. Heilongjiang changed from increasing to decreasing, while Guangxi changed from decreasing to increasing.

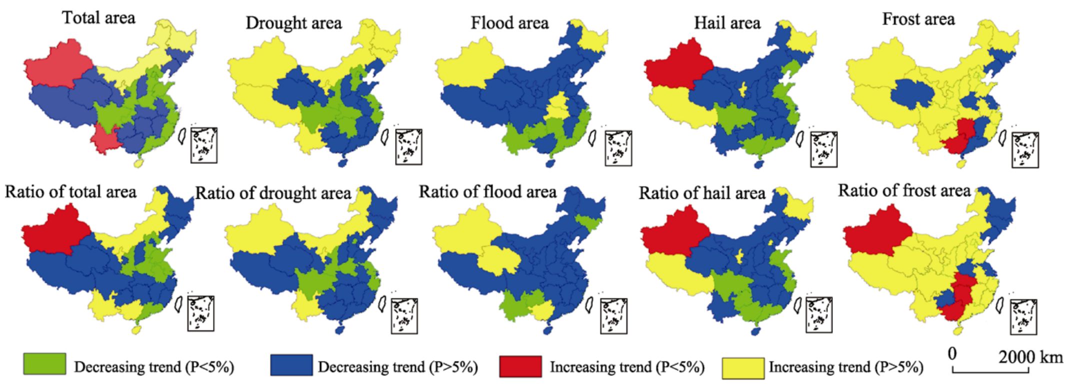

Figure 4 M-K tests of disaster areas and ratios of disaster areas

3.2 Effects on grain production

As shown in Figure 1, there was at least 32.5×10^6 ha, accounting for 29.4% of the sown area, affected by disasters during the study period. In particular, almost all major grain producing areas were located in the sub-hot spot areas, except Inner Mongolia (Figure 2). Furthermore, a CV of 0.21 indicated that grain production was instable, which suggested that disasters may threaten China's food security. This result was similar with those of previous studies. It should be noted that the area covered by disasters depended not only on the intensity of the disasters, but also on the sown area. Hot spot areas of disasters merely reflect the overall situation of grain production affected by disasters. In other words, the disaster areas cannot quantify the relative impact of disasters or the sensitivity of grain production to disasters. Per unit area grain yield change can provide a direct response to the impact of disasters. In order to evaluate the effects on grain production, the linear regression model was employed to analyze the relative influence, and the results show that disasters played an important role in per unit area grain yield (Table 3). The regression coefficient (β) was less than 0, indicating that disasters had negative effects on grain production, which would lead to a reduction of per unit area grain yield.

Table 3 Summary of linear regression analysis of disasters' effects on per unit area grain yield

Area	β	Adjusted R^2	P	Area	β	Adjusted R^2	P
China	–0.756	0.551	0.000	Henan	–0.654	0.399	0.001
Beijing	–0.071	0.000	0.847	Hubei	–0.560	0.279	0.007
Tianjin	–0.741	0.526	0.000	Hunan	–0.213	0.000	0.342
Hebe	–0.700	0.464	0.000	Guangdong	–0.474	0.185	0.026
Shanxi	–0.820	0.656	0.000	Guangxi	–0.350	0.079	0.110
Inner Mongolia	–0.027	0.000	0.903	Hainan	–0.168	0.000	0.454
Liaoning	–0.779	0.598	0.000	Sichuan	–0.698	0.461	0.000
Jilin	–0.770	0.573	0.000	Guizhou	–0.672	0.424	0.001
Heilongjiang	–0.521	0.235	0.013	Yunnan	–0.362	0.088	0.098
Shanghai	–0.217	0.000	0.332	Tibet	–0.255	0.018	0.252
Jiangsu	–0.770	0.572	0.000	Shaanxi	–0.857	0.720	0.000
Zhejiang	–0.655	0.400	0.001	Gansu	–0.451	0.164	0.035
Anhui	–0.719	0.479	0.000	Qinghai	–0.673	0.425	0.001
Fujian	–0.601	0.329	0.003	Ningxia	–0.071	0.000	0.754
Jiangxi	–0.253	0.017	0.256	Xinjiang	–0.386	0.107	0.076
Shandong	–0.833	0.679	0.000				

The values of adjusted R^2 varied from 0 to 0.720, denoting that the sensitivity of grain production of each province was quite different. Especially in some major grain producing areas, such as Shandong, Liaoning, Jilin and Jiangsu, the adjusted R^2 was larger than 0.572, while the adjusted R^2 of Inner Mongolia was 0.017. This suggests that provinces which were seriously affected by disasters, especially those in major grain producing areas, should allot greater amounts of financial and policy support to increase agricultural resilience. Overall, the adjusted R^2 of China's average per unit area grain yield was as high as 0.551, which indicated that 55.1% of the per unit area grain yield change was caused by disasters.

It should be noted that the value 0 did not suggest that disasters had no effects on grain production. The possible reason for the significant difference among adjusted R^2 was that per unit area grain yield may be improved by increasing agricultural material inputs and technical progress, such as agricultural infrastructure development, chemical fertilizer, and good seed (Neumann *et al*., 2010; Zhou *et al*., 2012). For example, it has been widely accepted that water conservancy construction may increase agricultural resilience and promote agricultural development. However, infrastructure construction projects typically require large amounts of funds, which was a great obstacle for individual farmers under the current household responsibility system. Meanwhile, grain production may be marginalized when the economy underwent rapid development, the typical characteristics were cropland and labor loss. Liu *et al*. (2005) found that a large amount of cropland was occupied by built-up land in the Yangtze River Delta, Huang-Huai-Hai region and Sichuan Basin, while large areas of the new cropland were converted from other land use types in northern and northeastern China. Long *et al*. (2010) pointed out that loss of rural labor may be a major issue of rural development, and along with cropland and labor loss, agricultural inputs may also be reduced (Gao *et al*., 2006), which would lower down grain production's ability to withstand disasters. This was one reason that Jiangsu and Shandong, which are among the most developed provinces of China, had high adjusted R^2.

4 Conclusions

This study explored the spatial pattern change of major agriculture disasters in China and the results indicated that grain production in China was severely affected by disasters. The main conclusions were as follows:

(1) The annual area covered by disasters reached 48.7×10^6 ha during the study period, accounting for 44.8% of the total sown area. Meanwhile, disasters fluctuated dramatically, which resulted in grain yield instability and food security issues. Generally speaking, the most serious disaster types in China were drought, followed in the order of flood, hail, frost and typhoon. All of the disasters showed high variability and different changing trends. Drought, flood, and hail showed significantly decreasing trends, while frost and typhoon showed increasing trends. Due to the geographical environment, the spatial distribution of each disaster was uneven. Drought and flood showed a gradual change and were distributed across the country. Drought was the dominant disaster type in northern China, while flood was most important disaster type in the southern part. Hail was mainly located in central and northern China, and frost was mainly distributed in southern China. The distribution of typhoon was quite different from the other disasters. It was considerably concentrated and was greatly limited to the southeast coast of China. Furthermore, the Moran's I changed year by year, indicating that the spatial pattern of disasters also changed along with time.

(2) Disasters had negative effects on grain production, causing a large fluctuation in per unit area grain yield. The results indicated that about 55.1% of per unit area grain yield change in China was caused by disasters during the study period. The effects of disasters on each province were quite different. The values of adjusted R^2 varied from 0 to 0.72, and the larger the adjusted R^2, the worse the resilience of grain production. In particular, some major grain producing areas, such as Shandong, Liaoning, Jilin and Jiangsu, were very seriously affected by disasters, which would threaten China's food security. It should be noted that the

economic development did not enhance the resilience of grain production, as China is currently undergoing rapid urbanization and industrialization. Jiangsu and Shandong were typical regions, and are among the most highly developed provinces in China, but grain production there was seriously affected by disasters, and the adjusted R^2 was greater than 0.572. In brief, reducing disaster risk and mitigating the impact of disasters are very important for China's agricultural development and grain security. One reason for the difference of resilience in grain production was that grain production was marginalized in developed provinces when the economy was undergoing rapid development. Therefore, governments should place more emphasis on grain production and invest more funds in disaster prevention and mitigation, especially in the major grain producing provinces.

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