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Effects of Climate Extremes on Cereal Production in the North China Plain During 1950–2015

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Abstract: The North China Plain (NCP) is a cereal production base in China. However, the understanding of how climate extremes affect cereal production during past decades in the region is limited. Based on the statistical data of climate disasters and cultivated areas during 1950-2015, the relationship between regional cereal production and four meteorological disasters was examined. The results showed that during 1950-1980, the cultivated area for cereal production increased, accounting for 80-85% of the total cultivated area, but gradually decreased in the second 30 years after 1980. Flood disaster was the greatest in intensity compared with the other three meteorological disasters; drought was the most widespread and impactful. The effects of the four disasters became more noteworthy after 1980, and the spatiotemporal trend in the NCP was similar. Flood and drought had significant effects ($P < 0.01$) on cereal yield with path coefficients of -0.355 and -0.344, respectively. The harvest areas declined slowly and the yield increased slightly during the 7 disaster window years, suggesting that technology advancement offset the decline in cultivated areas and increased the yield. The effect of climate extremes on cereal production could be addressed through technology improvement and the implementation of preventive measures in the NCP.

Keywords: Cereal Production, Drought, Flood, Effects, Decades, China

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1. Introduction

Climate change is a major issue affecting the sustainable development of agriculture worldwide and China in particular. According to the 5th Assessment Rreport of Intergovernmental Panel on Climate Change (IPCC AR5), the global average surface temperature has increased by 0.85°C from 1880 to 2012, and it is predicted to continue to increase [1]. Owing to the increase in temperature, the frequency, intensity, and impact range of extreme weather and climate events, such as droughts, floods, and heat waves, have increased, resulting in socio-economic and ecological losses [2]. China is one of the countries faced with serious meteorological disasters, such as increased frequencies of extreme weather and climate events. The average arable land affected by drought was approximately 24 million hm^2/a, accounting for an annual grain loss of approximately 26 million tons, i.e., about 5.2% of the total grain production in China [3-4]. The overall economic loss caused by meteorological disasters ranged over 1-3% of the total GDP in 2004-2013 [5]. There are wide concerns that with the increase in global warming, extreme weather events will increase in frequency and intensity, which will have profound effects on food security in China [6].

The North China Plain (NCP) is a substantial national producer of cereals in China, accounting for 40% of the country's annual cereal production, and thus plays a key role in ensuring national food security [7]. The NCP is located in a monsoon climate zone and is characterized by a fragile climate and frequent extreme weather events [8]. Agricultural disasters in the NCP have some specific chronological and regional characteristics [9]. In 1951–2020, drought has been the main factor affecting grain production in the NCP [10]. Owing to global warming, drought has become the recurrent meteorological disaster in the NCP in the last 20 years, resulting in the scarcity of irrigation water [11]. Furthermore, the amount of precipitation in the NCP has decreased slightly; the frequency of flood disasters have relatively decreased in the last 60 years [12]; however, over 1950–2000, there were 16 years of flooding events, of which 10 years of these events occurred before 1980 [13]. Several studies have shown that the intensity of extreme cold events has decreased whereas that of crop cold disasters has increased [12]. Owing to global warming, the frequency of extremely low temperature is expected to increase and may occur in spring, summer, or autumn with extensive damages. The occurrence of extremely low temperatures in the NCP is periodic, differs with regions, and may cause considerable loss of grain production, especially in late spring [14]. A warm winter usually promotes the productivity of winter wheat, whereas a low temperature in spring can cause frost damage and negatively affect wheat production, which will lead to tremendous economic losses [15]. During 1986–2005, extremely low temperature affected an area of about 3 million hm^2 in the Shandong and Henan provinces of the NCP. The intensity and effect of low temperatures were high during 1992–1999 and remained so until 2005 [16]. The occurrence and frequency of low temperature events reduced over time in China; however, Henan and Shandong province were severely affected by low temperature disasters with frequency ranging over 30–70% [17]. The damages due to low temperature disaster events are generally higher in the northern region than in the southern region of the NCP [10]. In the past decades, crop productivity was increased through the application of fertilizers, improved agronomic practices, and new crop cultivars. Furthermore, the adaptation of crops to warming climate also increased productivity [18]. However, in recent years, the occurrence of agriculture disasters, owing to global warming and water scarcity, considerably affected cereal production [19]. Observational studies have shown that the effects of extreme events have become more severe over time, resulting in an increased demand for irrigation water and the overuse of groundwater in provinces that practice wheat-maize rotation system in the NCP [20]. An alert was issued to explore the tendency, characteristics, and patterns of the disasters that influence the crop production [21].

Whether climate extremes can cause disasters depends not only on their severity but also on the vulnerability and exposure of humans and natural systems [22]. However, the inter-annual and inter-decadal characteristics of climate disasters and their effects on grain production remain unclear [23]. Relatively limited number of studies have assessed the effects of climatic disasters on crop production in the different provinces of the NCP [24]. Therefore, the aim of the present study was to examine the effects of extreme weather events on cereal production in areas in the NCP with typical wheat-maize rotation system using records of crop yield, cultivated area, and weather disaster during 1950–2015. The objectives of the study were to determine which extreme weather event was the most impactful on productivity and the decades and harvest areas that were most affected by disasters during 1950–2015. Additionally, we aimed to recommend preventive and coping measures for cereal production in the face of climate change.

2. Methodology

2.1. Description of Scope Area

The study was conducted in the NCP, which is located in latitude 31°14′- 40°25′ N and longitude 112°33′ -120°17′ E and is bordered to the north by Yan Mountain and to the east by Huai River. The NCP is a semi-arid humid zone with monsoon climate (Figure 1). The average annual precipitation range over 500–900 mm, and about 70% of the total rainfall is between the months of July and September. The eastern part is a transition zone between land and sea, and the southern part is a climate transition zone; thus, the NCP is characterized by a fragile climate and high incidence of extreme weather events. The NCP is densely populated, dominated by cultivated fields, and the major grain producing area in China. The cropping system comprise a winter wheat-summer maize rotation system with two harvests per year. Winter wheat is sown in early October and harvested in mid-June the following year, whereas maize is sown following the harvest of winter wheat and harvested in October. In this study, we selected three dominant provinces (Hebei, Henan, and Shandong) in the NCP that practice wheat-maize rotation system (Figure 1).

2.2. Data Collection

The statistical data of cereal crops planted during 1950-2015 were collected from the Planting Management Department of China Agriculture and Rural Affairs Ministry (MARA). The collected data were on the cultivated area, production, and yield of winter wheat and summer maize in the three provinces of interest. The agro-meteorological data were collected from the disaster database of the regional planting management division in each province. Areas with annual yield loss of more than 10% were considered disaster-exposed areas, whereas those with annual yield losses of more than 30% and 70% were classified as disaster-affected and no-harvest areas, respectively. Thus, disaster-affected areas were identified as areas with annual yield losses above 30%. When the ratio of disaster-affected area to cultivated area was more than 25%, the year was classified as a disaster year. When yield loss and area ratio met both set standards (annual yield loss of more than 30% and a ratio of disaster-affected area to cultivated area of more than 25%), then the year was classified as an agricultural meteorological disaster year. The study included disaster records of the three provinces during 1950-2015. The records comprised data of disaster-exposed, disaster-affected, and no-harvest areas for four major disasters, drought, flood, low-temperature, and wind-mails.

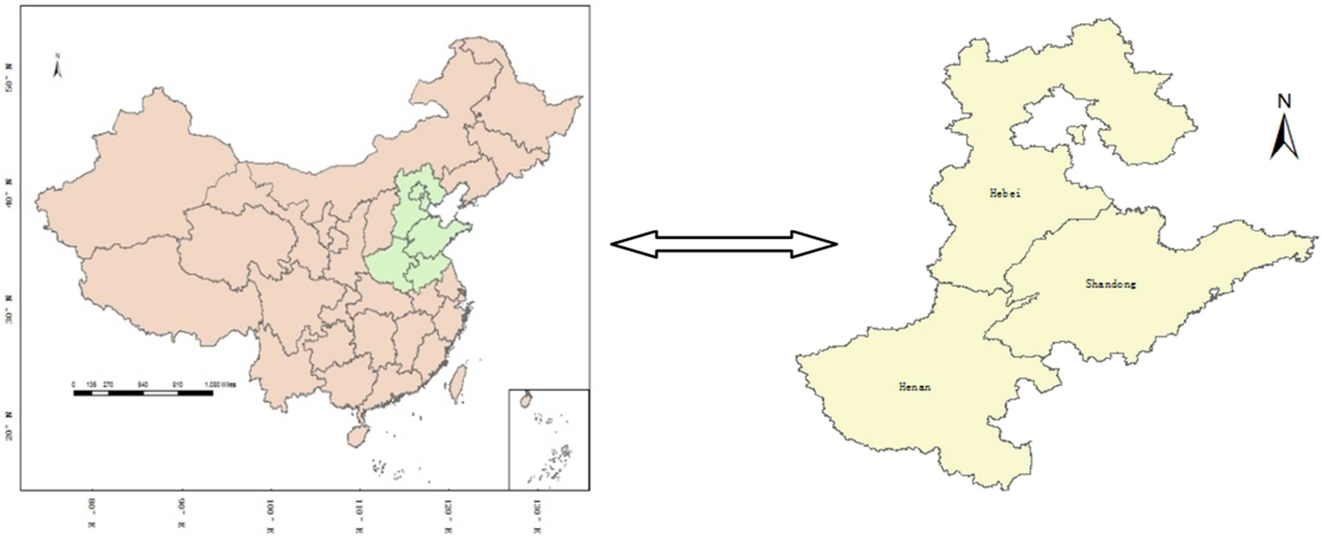

Figure 1. *The location of North China Plain (left) and the three major provinces with wheat-maize rotation system (right).*

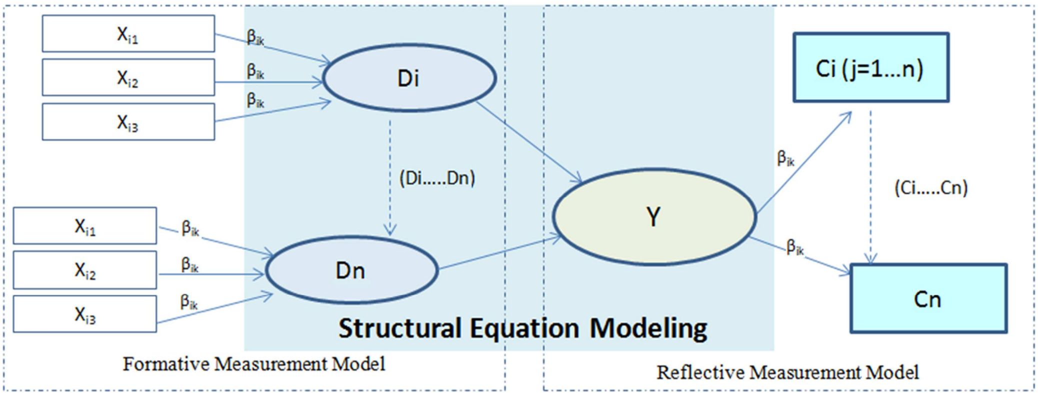

Figure 2. *Schematic diagram of structural equation model (X represents formative Indicator, C reflective Indicator, D exogenous latent variable, Y endogenous latent variable).*

2.3. Data Analyses

1) The ratio of the disaster-exposed area to the cultivated areas of cereal crops was referred to as the influence index of regional disasters ($H_{inf.}$), and the ratio of the disaster-affected area to the disaster-exposed area was referred to as the disaster intensity index at a certain period of time ($H_{int.}$).

$$\text{Influence index } (H_{inf.}) = A_{ie}/A_{ip}$$

$$\text{Intensity index } (H_{int.}) = A_{ia}/A_{ie}$$

where Aip is the planting area, Aie is the exposed area, and Aia is the affected area.

2) Superposed epoch analysis (SEA) was used to determine the effect of meteorological disasters on crop production within the examined timeframe. SEA is a nonparametric technique and has been used to test the statistical significance of associations and the effects of climate extreme events and disasters on various sectors [25-26]. In this research, SEA used a 7-year disaster timescale, and the data were normalized using an average of 3 years before the event and 3 years after the event to remove the effect (noise in SEA) of technologies and other factors to strengthen the disaster effects. In the crop production and disaster database, released by the MARA, some disasters were continuously recorded for more than 3 years, after that each year was separately isolated as one disaster event and was normalized as centered in 7-year windows. Furthermore, using the yield and harvested area data, we estimated individual effects of the different meteorological disasters on cereal production to identify the key driver of production losses.

3) The Structural Equation Modeling (SEM) method was employed to assess the relationships between yield (Y) and the disasters (D_i). The exposed areas (X_{i1}), affected areas (X_{i2}), and no-harvest (X_{i3}) areas were set as disaster formative indicators (D_i). The reflective indications (C_j) were denoted by summer maize and winter wheat and the importance of various indicators (D_i, C_j) with Y_k is expressed by path coefficient (β_{ik}, β_{jk}). The measure of direct and indirect effects of each disaster on cereal yield was estimated using a partial least square regression coefficient as path coefficient

analysis. Therefore, the correlation coefficient of different disaster variables for yield was partitioned into effects of disaster variables of different disaster areas. The path coefficients (β values) were computed using open-access R language package, and the estimated effects of relationships between variables and cereal yield were estimated [27].

3. Results

3.1. Cereal Planting Trends

The cultivated area for grain crops in the NCP showed an increasing trend in 1950–1980 and then decreased after 1980. In the first three decades (1950–1980), the area used for the cultivation of cereals accounted for 85% of the total cultivated area; however, this declined to 70% during 1980–2015 (Figure 3). The declining trend may be due to changes in the priority of cultivated crops. The result of M-K mutation test performed (α = 0.05) on the time series of the cereal planting areas showed that there was no mutation year in areas in the NCP region practicing wheat-maize rotation. The cultivated area for winter wheat production increased from 33% to 44% during 1950–1980 but remained at 47% for the next 25 years. The cultivated area for maize production increased considerably, especially from the 1990s, and the current rate of increase ranged over 5–7%/10a. Furthermore, in 2010-2015, the difference in the cultivated area for wheat and maize narrowed—47% and 41%, respectively (Figure 4). Overtime, the diet of humans has shifted from mainly plant-based to animal-based; therefore, the observed increase in maize production may be a result of an increase in its use in livestock nutrition and in industries. The cultivated area for wheat production has continuously declined; this may be a result of water scarcity and high demand for irrigation water, which is evidenced by the overexploitation of groundwater in the last 20 years.

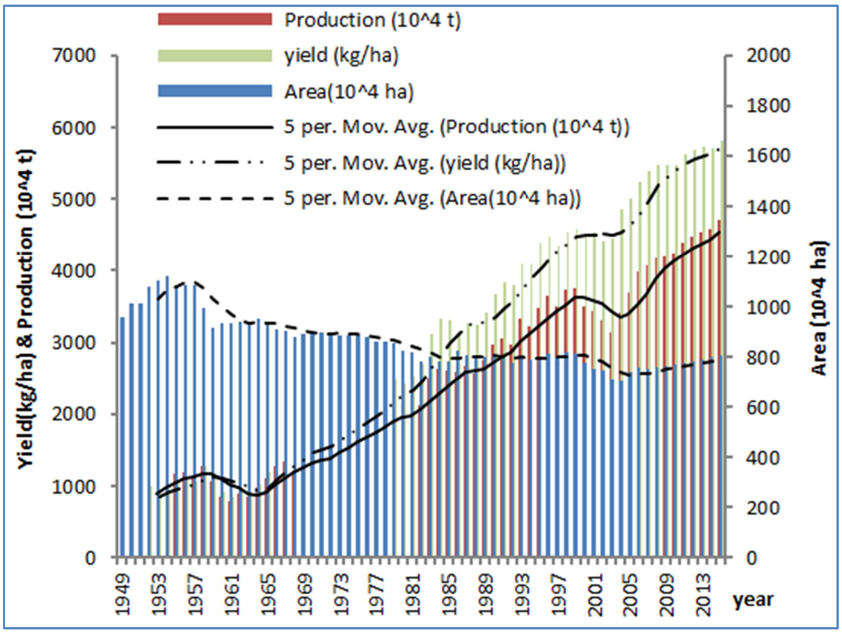

Figure 3. *Changes of Cereal Productivity from 1950-2015 in North China Plain.*

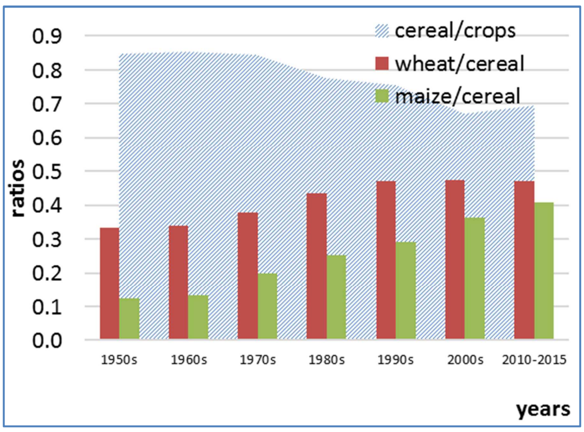

Figure 4. *The ratio changes of crops planting areas from 1950-2015 in North China Plain.*

3.2. Frequency of Disasters

In the present study, the ratio of the exposed areas of the meteorological disasters (drought, flood, wind-hail, and low temperature) to total cultivated area for cereal crops was more than 0.5 (50%), which represents an agricultural meteorological disaster event. The agro-meteorological disasters — drought, flood, wind-hail, and low temperatures — had marked effects on cereal productivity in the NCP. Historical data showed that the four agro-meteorological disasters affected the provinces in the NCP practicing wheat-maize rotation system approximately 450 times at a rate of 6-7 times per annum during 1950–2015 (Figure 5). The number of disasters increased by 30 times in the 1950s and by approximately 100 times in the 1990s. The highest number of disasters were recorded in the 1990s. Overall, disasters in the

NCP became highly frequent after 1980, and this may be due to the increase in global warming and advances in disaster monitoring technologies.

In terms of spatial differences, the frequencies of the disasters were higher in the three provinces examined during 1980–2010 (Figure 5). The disasters occurred 154 times in Hebei province and 146 times in Henan province and Shandong province during 1951-2015. Overall, the frequencies of drought and flood were the same in Hebei, followed by wind-hail and low temperature. Similarly, the frequencies of the disasters were the same in Shandong province and Henan province, and the order was flood> drought > wind-hail > low temperature. The flooding frequency was slightly higher than that of drought, and this may be because the provinces had lower resistance to flood than to drought. In the NCP, regional flood disasters mainly affected the growth of summer maize in wheat-maize rotation system.

Throughout the 65 years examined, the frequency of flood disasters reduced by 1.1 times/10a, drought increased by 0.8 times/10a, whereas that of wind-hail and low-temperature significantly increased by 2–3 times /10a. The frequency of drought disaster has gradually become obvious, and the intensity and frequency of extreme temperature related disasters have increased, which is consistent with regional climate warming. The wind-hail disaster has a high intensity but short occurrence time. The frequency of the different disasters indicated that precipitation has decreased and temperature variability has increased in the provinces in the NCP where wheat-maize rotation system is practiced.

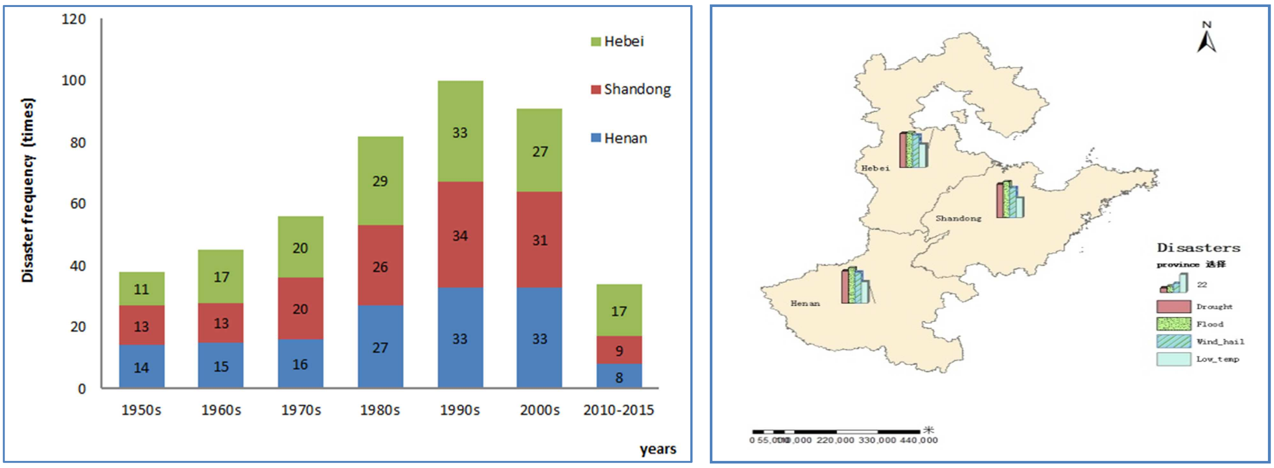

Figure 5. *The disasters frequency (left) and different disaster (right) in each province from 1950-2015.*

3.3. Influence of Disasters on Cereal Planting Areas

For the first three decades (1950–1979), the percentage of no-harvest and affected areas by the four disasters ranged over 0–1%; however, during 1980–2015, the percentage increased, i.e., 9–13%. This indicated that extreme events became more severe in the last 30 years of the period in consideration (1950-2015). The disaster affected areas were higher during 1960–2000, however, it has declined in recent years, and this may be due to technological advancements and the implementation of disaster prevention and management policies. After the 1980s, records of disaster-affected and no-harvest areas increased in frequency (Figure 6).

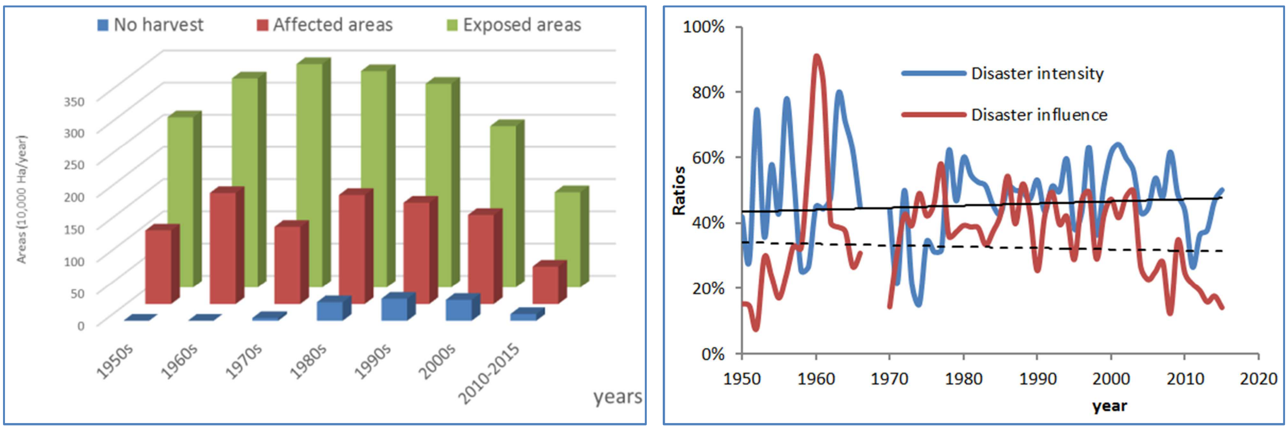

Figure 6. *Disasters area of cereal crops (left) and the indexes of influences and intensity (right) in NCP.*

In terms of the damages by the disasters, irrespective of the influence and intensity indices, the most damages were recorded in 1960, with disaster influence and intensity indices of more than 75% and 50%, respectively (Figure 6). The disaster intensity was low in the 1970s, with an intensity index of 35.8%. The lowest disaster influence index was recorded during 1978–1985, with an influence index of approximately 38%. Generally, in the NCP, the overall influence and intensity of the disasters were the highest in the 1960s and the lowest in the 1970s. During 1985–2005, disaster influence and intensity indices were approximately 50% and 43%, respectively; however, during 2005–2015, disaster influence index reduced to 20%, whereas intensity index increased to 45%. On the average, the influence of disasters has declined in the 21st century; however, approximately 45–50% of disaster-exposed areas have become disaster-affected areas.

Over the past 60 years, the total disaster-exposed and -affected areas of the four disasters in the three provinces were 4242.5 hm^2/a and 2017.7 hm^2/a, respectively, and approximately 50% of the total disaster-exposed areas have become disaster-affected areas. The landmass of the exposed areas of the four disasters are in the order of drought > flood > wind-hail > low temperature, where the exposed areas of drought and flood were 5.26 million hm^2/a, and 2.03 million hm^2/a, respectively (Figure 7). When the ratio of the exposed areas of each disaster to the total exposed area of the four disasters was considered, drought disaster had the largest proportion (62.0%), followed by flood disaster (24.0%), and the least was low temperature disaster (3.9%). However, when the ratio of each disaster-affected area to the total disaster-affected area was considered, the ratio was in the order of flood > wind-hail > drought > low temperature, where floods accounted for the largest damage (62%), followed by drought and hailstorm (43-45%), and the least was low temperature (33%). The flood disaster was greater in intensity than drought, but the effect of drought was more widespread. Regarding the inter-decadal effects of the four disasters, the drought had the greatest effect on both disaster-exposed and -affected areas. The exposed area of drought increased steadily and peaked in the 1980s but declined afterwards, which may be due to the improvement in drought prevention and management measures in the NCP after 1980.

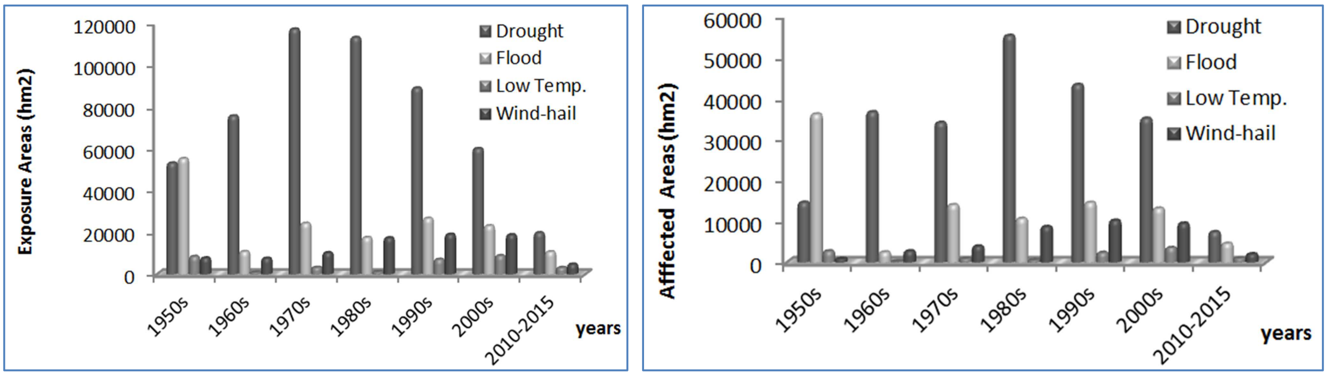

Figure 7. *Changes of disaster-exposed and affected areas by different disasters in the NCP.*

3.4. Influence of Disasters on Cereal Productivity

Based on data of cereal production, including annual cereal output and harvest area, SEA was used to evaluate the influence of the disasters on cereal production in the three provinces. The results showed a slight increase in cereal production during the 7 disaster years, whereas a slightly decreasing trend was recorded at the end of the 7 disaster years (Figure 8). Furthermore, the results indicated that total production was not significantly influenced by the disasters; however, disaster may have caused a fluctuation in output, which had a high recurrence in the subsequent years.

Crop yield showed an increasing trend during the 7 disaster years, and this may be due to technological advancements. However, the rate of increase was 2.9%/a during the disaster years compared with an average rate of 3.6%/a during 1950–2015, which indicate that disaster reduced the rate of yield increase by approximately 20%.

The disasters caused a decline in harvest area during the 7 disaster years. The observed decline in harvest area may be due to a decline in cultivated area as a result of civilization. The rate of decrease was 0.53%/a in the disaster years compared with an average rate of 0.23%/a in the normal years during 1950–2015. The difference in the rate of decrease suggests that the disasters caused a more extensive loss in harvest area; the reduction in harvest area doubled during the disaster years.

SEM can be used to estimate the relative contribution of each component for total determination. The exposed, affected, and no harvest areas were aggregated as potential variables of meteorological disasters. The effect of climate extremes on crop yields in the three provinces practicing wheat-maize rotation system was comprehensively analyzed using SEM with the partial least square regression method. The results showed that floods and droughts significantly influenced ($P<0.01$) yield, with path coefficients of -0.355 and -0.344, respectively (Figure 9). Drought-affected and no-harvest areas were the main components of potential drought variables with path coefficients of 0.864 and 0.816, respectively. The drought-exposed areas had a small contribution to the potential variables of drought. This is because farmers often pump groundwater for irrigation to relieve drought stress, which reduces the effect of drought on yield. Flood-exposed and no-harvest areas were the main components of the potential variables of floods, with path coefficients of 0.707 and 0.823, respectively. The disaster area indicators may be useful in the development of disaster response strategies. To overcome and manage the effect of drought, it is essential to focus on reducing the proportion of affected areas, and strengthening drought resistance. Similarly, it important to improve flood management to prevent and reduce the proportion of no-harvest areas; remediation during disasters is particularly critical. From the perspective of the effect of disasters on different crops, maize is more severely affected by climate extremes than wheat. With the adjustment of regional crop planting strategies, the proportion of maize production is gradually increasing.

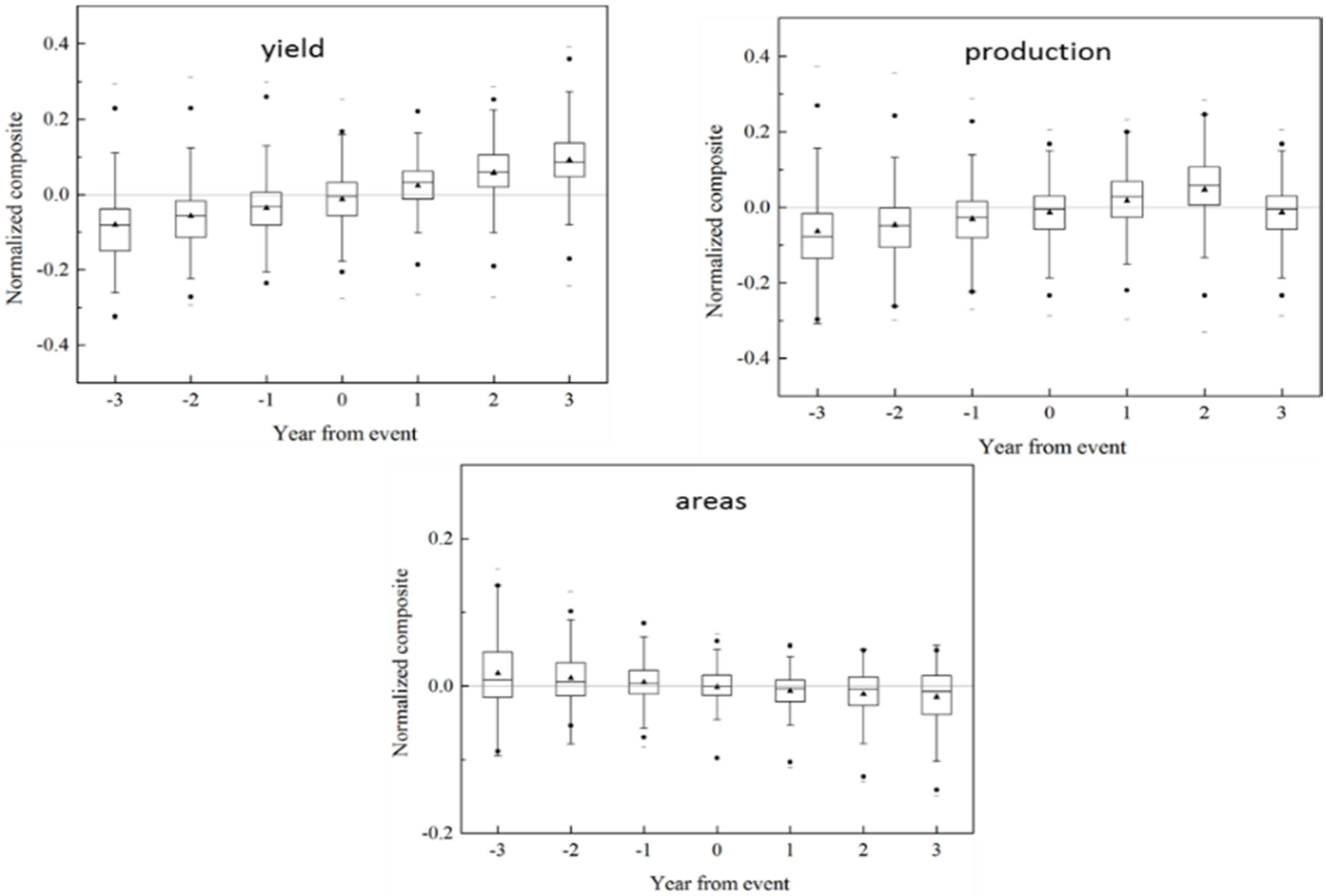

Figure 8. *The influence of disasters on cereal productivity with 7 years window of SEA in NCP.*

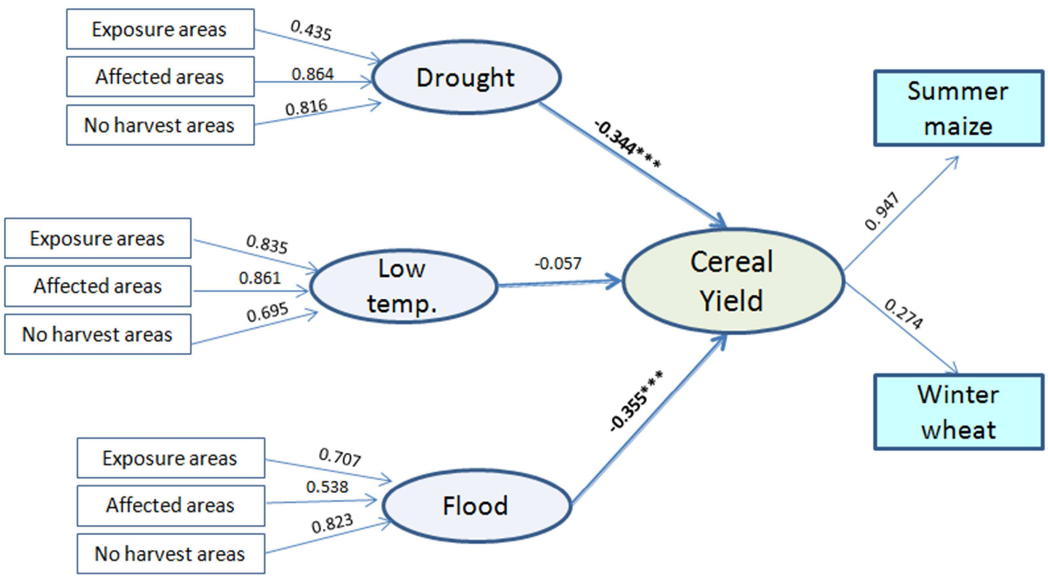

Figure 9. *Path models of climate extremes effects on yield (path coefficients were calculated from the Partial least squares regressions with R language).*

4. Conclusion and Discussion

4.1. Conclusion

Our study showed that during 1950–1980, the cultivated area for cereal crops increased but gradually declined after 1980. Additionally, the cultivated area for maize production showed an increasing trend after 1990, whereas that of wheat remained the same, and this can be attributed to the effects of climate change. It is concluded that the influence of the four disasters was in the order of drought > floods > wind-hail > low temperature, whereas the intensity was in the order of flood> wind-hail > drought > low temperature. Low temperature had the least frequency and affected area and did not markedly influence total cereal production, it had a high variability in the 7 disaster years examined, with an average standard deviations of 0.24, whereas wind-hail had a low variability, with a standard deviation of 0.084. Drought and flood disasters have a marked effect ($P<0.01$) on cereal yield of maize and wheat with path coefficients of -0.355 and -0.344, respectively. The harvest areas declined slowly and the yield increased slightly during the 7 disaster window years, suggesting that technology advancement offset the decline in cultivated areas and increased the yield.

4.2. Discussion

With the rapid development of China's economy, there is an increasing pressure on available resources and on the environment; thus, there is a need for the prevention of extreme weather events. Several studies have shown that the rate of climate change increased significantly in the NCP in 1980, and this may have increased the frequency and intensity of extreme weather events and consequently increased crop yield loss [28]. In the NCP, wheat production requires high use of irrigated water and has a longer growing season compared with maize. Contrarily, maize has a short growing season and a low requirement for irrigation, which may be the reason for the observed increase in its cultivation in the NCP [29]. Previous study has reported that the maximum and average temperatures in the growing seasons of cereal crops did not change significantly during 1992–2013 in the NCP, but the minimum temperature showed a significant increasing trend [30]. Ray et al. (2015) reported that temperature and precipitation variability was correlated with maize yield variability in the NCP [31]. In the present study, an increase in temperature was observed in all the provinces examined, with regions in Shandong province recording the most significant rise in temperature. The rate of temperature increase was relatively lower in Henan and Hebei provinces than in the Shandong province. Overall, it is observed that the minimums temperature rise is significantly higher than the maximum temperature and the average temperature. Approximately 7–10 million ha/a of cultivated land was affected by flood disaster, and meteorological disaster accounted for 27.5% of total grain loss. Torrential and heavy rainfalls have a great impact on losses [32]. In the NCP, wind-hail disasters occurred frequently in late spring and early summer and peaked in June. Hebei and Shandong are wind-hail prone areas, whereas southeast Henan province had fewer wind-hail disasters.

The change in the frequency of agricultural disasters was relatively consistent with the trend of climate change. In the NCP, from 1950, precipitation has been on a steady decrease, whereas temperature has been on a steady increase [33]. During 1981–2000, there was no significant change in average annual rainfall in the NCP; however, temperature has significantly increased within the same timeframe, thus making drought the most serious agricultural meteorological disasters in the NCP [24]. Metrological disasters have a substantially negative effect on cereal production in the NCP. Establishing and improving already existing agricultural disaster prevention and mitigation systems can improve the ability to cope with agricultural climate risks particularly under changing climate scenario [34]. Agricultural science and technology, social and economic systems, and agricultural policies also affect grain production [35].

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