The contributions of climate change and production area expansion to drought risk for maize in China over the last four decades

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Abstract
Maize is one of China’s most important crops and is profoundly sensitive to drought. Using weather and county-level maize yield data, the drought risk for maize in China was estimated for the period 1971–2010. The results show that drought risk has increased in China over the last 40 years, and that areas experiencing moderate to high drought risk have expanded, particularly in Northeast China. The main reasons for the observed changes are increased drought hazard associated with climate change, and increased exposure of maize to drought due to an expanded production area. Drought risk over all of China increased by 55% in the 2000s compared to the 1970s. While around 93% of the increase in drought risk in the maize production regions is due to increased drought exposure, 7% is attributable to climate change. In Northeast China alone, drought risk increased by 129% from the 1970s to the 2000s, which is the sum of an 86% increase caused by greater drought exposure, associated with expansion of the production area, and a 14% increase driven by climate change. The results indicate that the drought hazard has increased by around 13%, and drought risk has increased by 110% for each 1°C rise in annual mean temperature in Northeast China over the past 40 years. Maize yield losses have increased by around 4% per 1°C increase in annual mean temperature in this region. The sensitivity of maize to drought means that climate change is likely to have significant negative impact on future maize productivity, and China’s export and import of maize is likely to be affected.

KEYWORDS
China, climate change, drought risk, maize
1 INTRODUCTION

Agriculture is one of the pillars of China's economy. The agricultural sector employs 603.5 million people and contributes 8.9% to China's GDP (CSY, 2017). Maize is one of China's most important crops, with a total farming area of nearly 36.8 million hectares and production that exceeded 219.5 million tons in 2016 (CSY, 2017). Maize production in China constitutes a large proportion of global maize production (23% in 2016) (FAOSTAT, 2016), meaning that China's maize production strongly influences the world maize market. Over the past 60 years, China's maize production has increased approximately 10-fold due to increased yields and an increased production area. For example, maize production in 2016 was 14.2 times higher than in 1961, yields were 5.2 times higher and the production area increased by a factor of 2.7 (CSY, 2017).

China's climate is changing as the global climate warms (Song et al., 2010; Song et al., 2011; IPCC, 2013; Ren and Zhou, 2014). The annual mean air temperature in China has increased by 0.23°C-decade⁻¹ from 1961 to 2016, and the total precipitation has changed slightly over the same period, with larger changes experienced regionally (NCC, 2016). The number of drought events has increased, particularly in regions important for maize production (Fischer et al., 2011; Chen and Sun, 2015; Xu et al., 2015), and temperatures are projected to increase further in the coming century. The average temperature is projected to increase by 0.47 to 1.00°C between 2016 and 2035, relative to 1986–2005, assuming the emissions scenario described by Representative Concentration Pathway 4.5 (RCP4.5) (IPCC, 2013; Xu et al., 2018). In some parts of Northeast China in winter, and in central China in summer, precipitation is projected decrease between 2031 and 2050, relative to 1981–2000 (Wu et al., 2015). Given the direction of future climate change, it is very likely that maize production in China will be profoundly affected.

Climate change affects the physical, chemical, and biological processes that drive maize productivity. The growth of maize depends on temperature, precipitation and radiation, and anomalies in these, such as droughts that are induced by a combination of low precipitation and high temperatures, can have a disastrous effect on yields. Precipitation between June and August in 2014 was 20–50% below normal levels in Northeast China, which caused a 3.93 million ton decrease in maize production in Liaoning province (CMDY, 2015). A serious drought in parts of North China from February to July in 2000 severely impacted maize production; in Hebei province, an area of 1.54 million ha was impacted, and maize production was reduced by 0.94 million tons (CCIA, 2000).

Droughts are natural phenomena and can occur in any climate regime around the world, including deserts and rainforests. Droughts are a potentially expensive hazard, with significant and widespread impacts that affect many economic and social sectors. To monitor drought and to assess its impact, several drought indices have been developed (Palmer, 1965; Tarpley et al., 1984; McKee et al., 1993; Wu et al., 2001; Lyon, 2004; Narasimhan and Srinivasan, 2005; Nalbantis and Tsakiris, 2008; Vicente-Serrano and Lopez-Moreno, 2010; Anderson et al., 2011; Woli et al., 2012; Hao and AghaKouchak, 2013; Beguería et al., 2014). The standardized precipitation index (SPI) was developed by Thomas B. McKee in 1993 (McKee et al., 1993), and in 2009 the WMO recommended that the SPI, which is calculated only from precipitation, should be the main meteorological drought index used to monitor the evolution of drought conditions (Hayes et al., 2011). Another widely used index is the weighted average of the precipitation index (WAP) (Lu, 2009), which has been shown to perform better than the SPI, on which it is based, as it is more flexible and can be applied over different timescales (Lu et al., 2014). The Palmer drought severity index (PDSI) was originally developed for North American conditions by the U.S. Weather Bureau in 1965 (Palmer, 1965; Alley, 1984) and is one of the most widely used drought indices worldwide. The standardized precipitation and evapotranspiration index (SPEI) takes into account both precipitation and potential evapotranspiration, so that, unlike the SPI (on which it is based), it captures the impact of increasing temperatures on water demand (Vicente-Serrano and Lopez-Moreno, 2010). Several studies have examined changes to drought and the degree to which these are driven by global warming (Dai, 1998; Ma et al., 2004; Sheffield and Wood, 2008; Qian, 2011; Wang et al., 2011; Sheffield et al., 2012; Dai, 2013; Trenberth et al., 2014; Dai and Zhao, 2016). However, only limited research has been carried out into the contribution of climate change to agricultural drought risk, particularly for China.

In the present study, a risk framework is used to assess the changes to drought risk for maize production in China experienced over recent decades. Weather data from observations and national data on maize yield and production area are used to map maize drought vulnerability and the drought hazard, as well as the exposure of maize production areas to climate change from 1971 to 2010. Section 2 describes the study area, data and methodology used for this study. Section 3 presents the results...
of the risk mapping. Finally, Section 4 summarizes the study and presents our conclusions.

2 | MATERIALS AND METHODS

2.1 | Study area

The major maize-growing regions in China are located in the east, particularly in Northeast China (NC, including the provinces of Heilongjiang, Jilin and Liaoning), on the North China Plain (NCP, including the provinces of Hebei, Henan, Shandong, Shanxi) (Figure 1), and in Inner Mongolia and Shaanxi. In these 9 provinces, the arable maize area was 402.4 million hectares in 2016, which was 73% of the total maize production area in China (CSY, 2017). However, maize is also planted in other provinces, and so our study area covers all of China, including temperate, semi-humid and monsoon-controlled climatic zones. Total annual precipitation generally ranges from 286 to 575 mm in NC, from 451 to 598 mm in NCP, and from 1,000 to 2,075 mm in southern China, depending on topography and on atmospheric circulation patterns. Frequent droughts and low temperatures can damage maize in spring and summer.

2.2 | Data

To investigate changes to maize drought risk and the contribution of climate change to these changes, daily precipitation data from the China Meteorological Administration for the period 1971–2010 were used. Meteorological data covering periods longer than 40 years with low rates of missing data (≤5%) were selected from stations in counties where maize is grown. This meant that data from 1,850 out of 2,540 stations were used for the analyses. Data on maize yields and production area were provided by the Ministry of Agriculture for the People’s Republic of China at a county level for the analysed period. To investigate the effectiveness of the WAP index for capturing drought stress, we used observations of relative soil moisture from the eighth, 18th and 28th of every month from 2000 to 2001 at 110 agro-meteorological observation stations without irrigation or plastic mulch.

2.3 | Methods

2.3.1 | Drought index WAP

Because the WAP index has been shown to be more flexible and applicable on different timescales...
(Lu et al., 2014), and has been successfully used when analyzing the impact of drought on maize in China (Song et al., 2019), we chose it for our analysis. Drought variability can be described by a simple physical model using only precipitation. The model is expressed as.

\[
\frac{df(t)}{dt} = -bf(t) + P(t)
\]  

(1)

where \(t\) is the time, \(f(t)\) is drought intensity at time \(t\), \(P(t)\) is precipitation at time \(t\), and \(bf(t)\) is the impact on the drought extent from the demands of runoff, evapotranspiration, groundwater flow, and percolation (Lu, 2009).

The WAP is defined as follows:

\[
WAP = \sum_{i=0}^{N} a^i p_n \sum_{a=0}^{N} a^e
\]  

(2)

where \(N\) is the total number of the earlier days over which the WAP is calculated; \(n\) ranges from 1 to \(N\); and \(a = e^{-\Delta t} < 1\) represents the contribution of the previous day's precipitation, \(P_1\), to the present day drought extent, \(f_0\). The SPI (standardized precipitation index) and present-day precipitation can be considered equivalent to the WAP for the extreme cases of \(a = 0\) and \(1\), respectively. As \(a\) approaches zero, the WAP tends to \(P_0\) and when \(a = 1\), the WAP is equivalent to the simple average of precipitation. In this paper, WAP was standardized. A detailed description of the index is presented in Lu (2009).

2.3.2 Drought risk

In this work, the drought risk for maize was defined as the product of hazard, vulnerability and exposure according to natural disaster risk theory (UNDP, 2004; Dilley et al., 2005; IPCC, 2012; Zhang et al., 2015):

\[ R = H \times E \times V \]  

(3)

In Equation (3), \(R\), \(H\), \(E\), and \(V\) are the risk, hazard, exposure, and vulnerability.

\[ H = \frac{D}{D_{\text{max}}} \]  

(4)

Drought hazard is the degree to which the drought is anomalous. For this work, hazard was calculated from the number of days for which the WAP exceeded the WAP limit. The influence of drought on maize growth is complicated, as short periods of drought may have a slight negative short-term impact on growth, while long periods of drought may have long-lasting negative effects on maize growth that cannot be compensated by later rain and may result in reduced yields. Consequently, drought days are very important for maize growth. Drought hazard was calculated from the ratio of the number of drought days (\(D\)) to the historical maximal number of drought days (\(D_{\text{max}}\)), where \(D_{\text{max}}\) is the maximum number of drought days experienced in a single maize growth period between 1971 and 2010 at all stations.

\[ E = \frac{A_m}{A_i} \]  

(5)

Exposure refers to the extent of the maize production area that is threatened by drought. A larger exposed area corresponds to a greater potential maize yield loss. Maize yields are greatly affected by drought that occurs in regions where more maize is cultivated, but are affected only slightly by drought in regions with little maize production, and this is reflected in the Exposure measure. Exposure was given by the ratio of the maize production area (\(A_m\)) to the total land area (\(A_i\)) of a county.

\[ V = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^{n} (X_i - \bar{x})^2}}{\bar{x}} \]  

(6)

Vulnerability refers to the degree of damage or loss caused by a drought. In general, a greater vulnerability means that, in the event of a drought, the potential maize loss attributable to the drought is greater. The vulnerability is related to the characteristics of the maize and to how easily drought can be prevented or its impacts mitigated. Maize is irrigated in some regions of China, for example in the Henan province, and the use of plastic mulch to reduce evaporation is common in some regions, for example in Gansu. In parts of NC and the NCP, maize is cultivated without irrigation or plastic mulch and the impact of drought therefore depends on the site conditions. Variability in maize yields is usually low for fields with irrigation or plastic mulching, but the impacts of drought can be high for fields without irrigation. Vulnerability was calculated from the coefficient of variation for maize yields. In Equation (6), \(n\) is the number of years, \(X_i\) is the maize yield in year \(i\), and \(\bar{x}\) is the average maize yield over the study period.

2.3.3 Yield loss rate

Maize yields are influenced by technological development (e.g., changes in the cultivated maize varieties or in
fertilization applications) and by climate. Maize yield losses are affected by weather events such as droughts, floods and extreme temperatures, as well as by plant diseases and insect pests. Since 1961, China’s maize production has increased around 10-fold, and yields have increased around five-fold (CSY, 2017). The increasing trend in yields has largely been driven by advances in agricultural technology, but the effects of these advances are quite short, for example a new variety usually increases yields for only around 3–5 years in China (Song et al., 2015). The yield loss rate was defined using Equation (7), which expresses the yield for a given year relative to the yield averaged over the preceding 3 years, as follows:

\[ Y_l = \frac{Y_i - Y_t}{Y_t} \times 100\% \]  

(7)

where \( Y_l \) is the yield loss rate, induced mainly by climate events. \( Y_i \) is the maize yield in a given year, \( i \). \( Y_t \) is the maize yield averaged over the 3 years preceding \( i \).

3 | RESULTS AND DISCUSSION

3.1 | Changes of maize drought exposure

The maize production area in China increased steadily between 1971 and 2010. The mean maize production area between 2001 and 2010 was 28.2 million ha, which represents an increase of around 150% from the 1970s to the 2000s (Figure 2). The lowest maize production area over the studied period was 16.5 million ha in 1973, and the highest was 35 million ha in 2010. The greatest expansion in production area was in NC and the NCP; for example, in 2010 the production areas in Heilongjiang, Jilin and Liaoning provinces were 4.4, 3.0, and 2.1 million ha, representing increases of 1.2, 1.0, and 1.1 times, relative to the respective 1971 production areas.

Drought exposure increased as the maize production area expanded. Figure 3 showed the increase in the number of regions with high drought exposure (>10%). In the 1970s, high drought exposure was restricted to a few regions in NC and the NCP, while in the 2000s, most regions of NC and the NCP were associated with high drought exposure. The results show that drought exposure for maize production areas had increased by 49.3% in the 2000s, relative to the 1970s. Notably, drought exposure increased by 98.3% in NC and by 64% in the NCP.

Temperatures in Northeast China are generally lower than in other regions in China, and the accumulated temperature (>10°C) was only 2,709°C in the 1970s, which was insufficient for maize growth (maize growth requires ca. 2,500–2,800°C). As the accumulated temperature increased to 2,899°C in the 2000s, conditions became more favourable for maize growth in NC. The first autumn frost, which could also affect maize yields, was delayed by 1–10 days in NC over the study period (Song et al., 2010), which further contributed to favourable maize growth conditions. Thermal conditions are important for maize growth, and the increasing accumulated temperature and delayed first autumn frosts both served to make conditions more favourable for maize growth in NC.

3.2 | Changes in maize drought hazard

The growth of maize depends on temperature, precipitation and radiation, and anomalies in these parameters, such as droughts, floods or extreme temperatures, can have disastrous effects on yields. The most common weather hazard for maize in Chinas is drought, caused by a combination of low precipitation and high temperature. We therefore focused on drought in this study, which we identified using the WAP index (see methods). Drought can influence maize yields strongly and negatively, for example, by affecting stomatal conductance, photosynthesis, leaf expansion, and progression of the plant cycle (Parent and Tardieu, 2014). Soil moisture may decrease in response to drought conditions, limiting the amount of water available to the maize root system. If drought conditions continue and maize then grows under water deficit conditions, then its growth is negatively impacted. First, the ability of the WAP index to capture drought stress was investigated, and then the WAP threshold for drought was calculated from relative soil moisture observations. The results show significant correlations between
the WAP index and relative soil moisture ($r = 0.76$, $p < .0001$). These results indicate that the WAP index effectively captures maize drought stress; and show that when WAP$_0$ was less than $-0.9$, the relative soil moisture was less than 60% (which is equivalent to maize roots being under water deficit conditions) (Figure 4). We therefore chose this value as the WAP threshold for drought events (the WAP limit). Using this WAP limit, the number of drought days during the maize growing season (May–September) was found, and the maize drought hazard was calculated.

Hazardous droughts were mainly driven by reduced precipitation, particularly in NC and the NCP. In the 1970s and 1980s, areas of high drought hazard were mainly confined to the provinces Hebei and Shandong in the NCP. In the following decades, areas associated with a high drought hazard expanded across China, although

**FIGURE 3** Drought exposure calculated for maize for each decade from 1971 to 2010 in China

**FIGURE 4** The relationship between the WAP drought index and relative soil moisture
the extent of these areas (areas with hazard values >0.4) varied through time and was greatest between 1991 and 2000 (Figure 5). Averaged over all of China, the drought hazard increased slightly (3.9%) from the 1970s to the 2000s, but it increased by 15.7% in NC. The greatest increase in drought hazard was therefore experienced in NC and the NCP. Given that 73.5% of China’s maize production is concentrated in these regions (43.5% in NC and 30% in NCP) (CSY, 2017), drought hazard in these regions profoundly impacts China’s total maize production. Irrigation from groundwater or from reservoirs can partly compensate for droughts in some regions in the NCP. However, weak irrigation infrastructure and poor access to water means that maize growth in NC can be severely affected by drought. For example, the 2001 drought in NC impacted on 2.7 million ha (55.2%) of crop area in Jilin province, affected 70% of crop land in Liaoning province (CMA, 2002), and resulted in maize production for two provinces for 2001 being only 80.1% of that in (CAY, 2002).

### 3.3 Vulnerability of maize to drought

If maize can access enough water through irrigation or from reservoirs or underground sources, or if plastic mulching is used to reduce evaporation, then yields are only slightly influenced during droughts. Taking the effects of irrigation and plastic mulching into consideration, the drought vulnerability of maize was defined using Equation (6).

The results show that the drought vulnerability was higher than in other regions in eastern Inner Mongolia, western Heilongjiang, Jilin and Laoning, and in the west

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**FIGURE 5** Drought hazard calculated for maize for each decade from 1971 to 2010 in China
of Gansu and Qinghai (Figure 6). In these regions, the maize yields had large fluctuations and irrigation conditions were poor. For example, the average drought vulnerability was only 0.19 in Henan province, which had good irrigation conditions, but it was 56% higher in Inner Mongolia, where irrigation conditions were poor. The average precipitation was only 274 mm during the maize growing season in Inner Mongolia, but was 555 mm in Henan province. The difference in precipitation made drought more likely for Inner Mongolia than for Henan. In 2000 there were only 457 water reservoirs in Inner Mongolia and 2,392 reservoirs in the Henan province, which could supply irrigation water in times of drought (CSY, 2001). It is therefore not surprising that the drought vulnerability of maize was found to be higher in Inner Mongolia than in Henan, given the more frequent droughts, weaker irrigation infrastructure and poorer access to water in Inner Mongolia.

### 3.4 The contribution of climate change to drought risk

The relationship between reductions in maize yield and drought risk is shown in Figure 7 for drought years. The results show that maize yields tend to decrease with increasing drought risk. A linear regression between the yield loss rate and drought risk, shows 27% of the variance in maize yield reduction is attributable to drought risk. Drought risk was categorized into no risk, mild risk, moderate risk and high risk based on the yield loss rate (Table 1), and the corresponding drought risk was then calculated using linear regression. For example, high drought risk was deemed to occur where the yield loss rate exceeds 30%, which corresponds to drought risk values of 0.04 and greater. The drought risk was therefore deemed to be high when it was 0.04 or greater.

Over the period 1971 to 1980, 70 counties in the Jilin and Hebei provinces experienced moderate maize drought risk, while between 2001 and 2010, moderate drought risk became more widespread and affected 155 counties in Heilongjiang, Jilin, Liaoning, Hebei, and Henan provinces. The eastern regions of Inner Mongolia
experienced high drought risk during 2001 to 2010 (Figure 8).

Figure 8 shows the drought risk experienced in different decades. It is clear that the number of regions that experienced moderate and high drought risk increased with time. The main reasons for this were the simultaneously increasing drought hazard and drought exposure. In summary, the results show that the drought risk increased by 55.1% in the 2000s compared to the 1970s over all of China (Figure 8). 92.7% of the increased drought risk was due to increased drought exposure for maize, and 7.3% was due to increased drought hazard, caused by climate change. The drought risk for Northeast China increased significantly, by 129.1% from the 1970s to the 2000s (Figure 8). 86.2% of this increase was due to greater drought exposure, and 13.8% was due to increased drought hazard, caused by changes in the climate over the study period.

Northeast China is the most sensitive agricultural area to climate change and annual average temperatures there have been continuously increasing, from 4.5°C in the 1970s, to 5.0°C in the 1980s, to 5.5°C in 1990s, and reaching 5.7°C during 2001–2010 (Table 2). Over the four

| Classification     | Yield loss rate | Drought risk limit |
|--------------------|-----------------|--------------------|
| No drought risk    | (0, 5%)         | (0, 0.00049)       |
| Mild drought risk  | [5%, 10%)       | [0.0005, 0.0079)   |
| Moderate drought risk | [10%, 30%)   | [0.008, 0.039)     |
| High drought risk  | [30%, 100%]     | [0.04, +∞)         |

**Figure 8** Drought risk calculated for maize for each decade from 1971 to 2010 in China
decades between 1970 and 2020, the annual average temperature has increased by 1.17°C. The drought risk in Northeast China increased by 129.1% over this period (Figure 8), corresponding to a 13.4% increase in the drought hazard. This is equivalent to an increase in drought hazard of 110.3% per 1°C increase in annual mean temperature for Northeast China over the past 40 years.

An increase in drought risk driven by climate change in Northeast China would affect maize yields and production, and subsequently influence the import and export of maize. In 2017, China exported 8.5 × 10^7 kg of maize, to which Northeast China contributed 8.0 × 10^7 kg, that is, 94.1% of China’s total export (CBIRI, 2018). This clearly shows the national importance of maize production in this region. Drought risk in Northeast China has increased, partly due to climate change, and maize yield losses were equal to 19.4% of the country’s total maize yield in drought years between 2001 and 2010 (Figures 7 and 8). These losses were 4.7% higher than those for 1971–1980. The results also show that maize yield losses increased by 4.0% per 1°C increase in annual mean temperature in Northeast China over the past 40 years.

4 | SUMMARY AND CONCLUSION

Using daily precipitation and the county-level maize yield and production area data, the drought risk in China between 1971 and 2010 was quantified, with the aim of estimating the contributions to this from climate change and from the expansion of production areas.

Maize drought risk depends on drought vulnerability, hazard, and exposure. The results show that drought exposure in the maize-growing regions of China increased by 49% in the 2000s compared to the 1970s. Specifically, it increased by 98% in NC, and 64% in the NCP. Over the same period, the average drought hazard for the whole of China increased by only 4%, but it increased by 16% in NC. Drought risk has increased in China over the last 40 years, and areas with moderate to high drought risks have expanded, particularly in NC. The two main drivers for the observed changes were an increase in drought hazard, attributable to climate change, and the increased exposure of maize crops to drought as production area has increased. The drought risk for all of China increased by 55% in the 2000s, compared to the 1970s. While around 93% of the increase in drought risk in the maize production regions was driven by increased drought exposure, 7% was due to climate change. In Northeast China alone, the drought risk increased by 129%; the combination of an 86% increase due to rising drought exposure, associated with expansion of the production area, and a 14% increase driven by climate change. Note that the WAP index does not account for evaporation, which increases with increasing temperature, and the calculated drought risk is therefore lower than it would be if evaporation was taken into account.

Northeast China is the most sensitive agricultural area to climate change, and the annual average temperature here has increased continuously over the last four decades. The results indicate that the drought hazard here has increased by 13%, and the drought risk has increased by 110% for each 1°C rise in annual mean temperature over the past 40 years. The maize yield losses in this region were equivalent to 19% of China’s total county-level maize yield during drought years between 2001 and 2010, and were 5% higher than the losses between 1971 and 1980. Maize yield losses in this region increased by around 4.0% for every 1°C increase in annual mean temperature. Maize exported from NC accounts for 94% of total maize exports from China. Climate change has already had a negative impact on maize yields in this region, and so impacted total maize exports from China. Given the sensitivity of maize production in northern China to drought, increasing temperatures are likely to have significant negative impacts on productivity in the future, meaning that China’s future export and import of maize will likely be influenced by climate change.

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